National Energy Board

AN ECONOMIC ANALYSIS OF GENERATION PATTERNS ON FUTURE POWER SYSTEMS

A Staff Study
by
Edwin A. Moore

OTTAWA, CANADA
JUNE, 1968

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UNE ANALYSE ÉCONOMIQUE DES TYPES DE PRODUCTION POUR LES RÉSEAUX ÉLECTRIQUES DE L'AVENIR

par

Edwin A. Moore

RÉSUMÉ

A l'avenir, les types de production d'électricité seront choisis de façon à remplir chacun un rôle particulier - l'énergie nucléaire comme source énergétique de base, les centrales thermiques (charbon, pétrole) comme source intermédiaire, les réservoirs remplis par pompage pour usage en période de pointe et les turbines à gaz pour accroître les capacités des groupes thermiques plus anciens. On a mis au point une méthode graphique pour déterminer quelle quantité d'énergie devrait provenir de chacune de ces sources.

En dehors des heures de pointe, l'énergie nucléaire servira à remplir les réservoirs par pompage. Les centrales nucléaires à eau lourde où le coût des sources énergetiques est peu élevé et les centrales à réservoirs par pompage se compléteront. Dans des conditions optimales, cette combinaison pourrait bien constituer un système de production énergétique complet.

Ottawa, Canada
Juin 1968

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ABSTRACT

On future power systems generation will be selected to fill specific roles - nuclear power as base generation, fossil plants as intermediate generation, pumped storage as peaking, and gas turbines as reserve to augment older fossil units. A graphical method of determining the relative amounts of these generation types is developed.

Pumped storage will utilize off-peak nuclear capacity as a source of pumping energy. Low-fueling-cost heavy water nuclear units and pumped storage plants will be highly complementary. Under optimum conditions this combination might constitute the entire system capacity.

Although this staff study paper is published under the auspices of the National Energy Board, the assumptions used and the views expressed are those of the author.

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June, 1968

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By Edwin A. Moore, National Energy Board

1. INTRODUCTION

Within the last decade a significant change has occurred in power system generation planning. As the full development of the economic hydro resources has neared most power systems have turned to some form of thermal power for further system expansion. Existing thermal systems have developed using a displacement pattern with new units being added as base generation, gradually rising in the load curve to act as peaking generation, and finally serving as reserve generation before retirement. Generation on future power systems will normally perform specific roles with nuclear units providing the base generation, traditional fossil units serving as intermediate generation, pumped storage plants supplying peaking and gas turbines acting as reserve to augment older fossil units.

This paper examines some of the generation and system characteristics that have brought about this strata planning of generation and illustrates a simple graphical approximation for analyzing future system costs to determine the optimum generation mix. The average generation costs for future power systems are predicted. Using the graphical

method the complementary system characteristics of pumped storage and heavy water nuclear generation are demonstrated.

2. CONVENTIONAL HYDRO

In terms of load-fitting characteristics, conventional hydro can be divided into three categories:

1) Base Generation - Where large reservoirs provide almost constant flow, the hydro plant output can serve as base generation. Two examples of base generation are the St. Lawrence River plants, where the flow is maintained by the tremendous Great Lakes storage system, and the Churchill Falls plant under development, where a 2700 square mile reservoir will assure an almost continuous flow.

2) Intermediate Generation - Many rivers have upstream "controlled" storage permitting seasonal regulation to average out the monthly flows and to provide energy at a 50% to 60% annual capacity factor. The river flow and water level requirements of other interests, such as navigation and log driving, present limitations which may prevent the use of this generation for peaking.

3) Peaking Generation - Where the requirements of other interests are not restrictive the off-peak river flows can be stored and utilized to provide peaking energy for a few hours each day. The Madawaska River plants in Ontario are examples of peaking generation.

USE OF CONVENTIONAL HYDRO GENERATION

FIGURE 1a

ALL-HYDRO SYSTEM

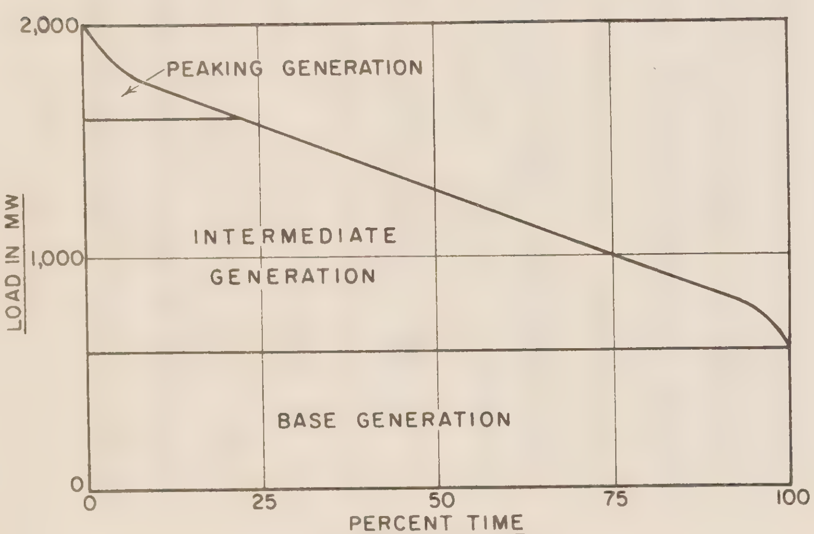


FIGURE 1b

EXPANDED SYSTEM

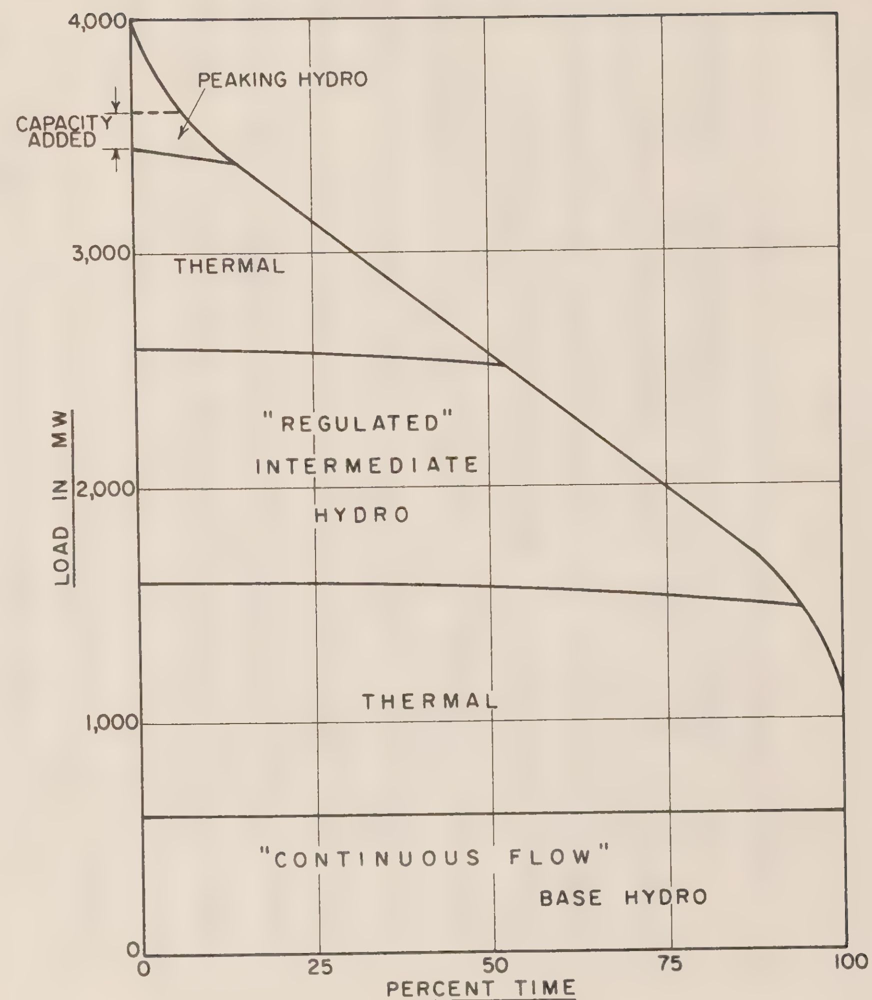


Figure 1 (a) shows these three categories of generation on an all-hydro system and Figure 1 (b) shows how they fit into the system when it is expanded with thermal generation. The future trend will be to reshape the peaking energy by the installation of additional capacity, thus supporting a larger section of the peak as the system peak narrows with load growth. Wherever possible existing intermediate generation plants will be redeveloped to provide peaking capacity. In future, except for hydro base generation, hydro plant capacity factors will trend downward.

Because hydro plants have low operating costs, hydro units are normally load-dispatched to optimize all advantageous features relating to capacity and energy as may be inherent in each particular block of hydro generation. Conventional hydro, present and future, will continue to play this role regardless of the later selection of other generation types. Once the investment in hydro has been committed, the operating costs of hydro generation in most cases is well below the operating costs of thermal or nuclear sources. Because of this low operating cost, hydro will seldom be displaced or discarded; it will continue to be utilized to the full energy capability regardless of the later selection of other generation types.

In North America most of the large hydro sites have been developed or are in the planning stages. The remaining economic hydro sites would provide only a small part of the future power requirements and in the long term conventional hydro generation will merely augment the predominant thermal and nuclear generation sources. A future decision to develop an available hydro site must be based on detailed studies of its economic worth relative to the thermal or nuclear alternative possible for that section of the load curve most advantageously suited to the hydro source.

While existing conventional hydro is fully accepted, for the purpose of simplification neither the existing nor the remaining hydro development possibilities have been included in the analysis which follows, although the method developed in the study could be used to analyze such hydro sources.

This particular analysis will deal with the selection of the main thermal sources of future generation with the object of minimizing the annual generation costs on the overall power system.

3. FOSSIL GENERATION

Many power systems in the United States and in Western Canada have developed based almost entirely on fossil-fired thermal generation. As these systems have

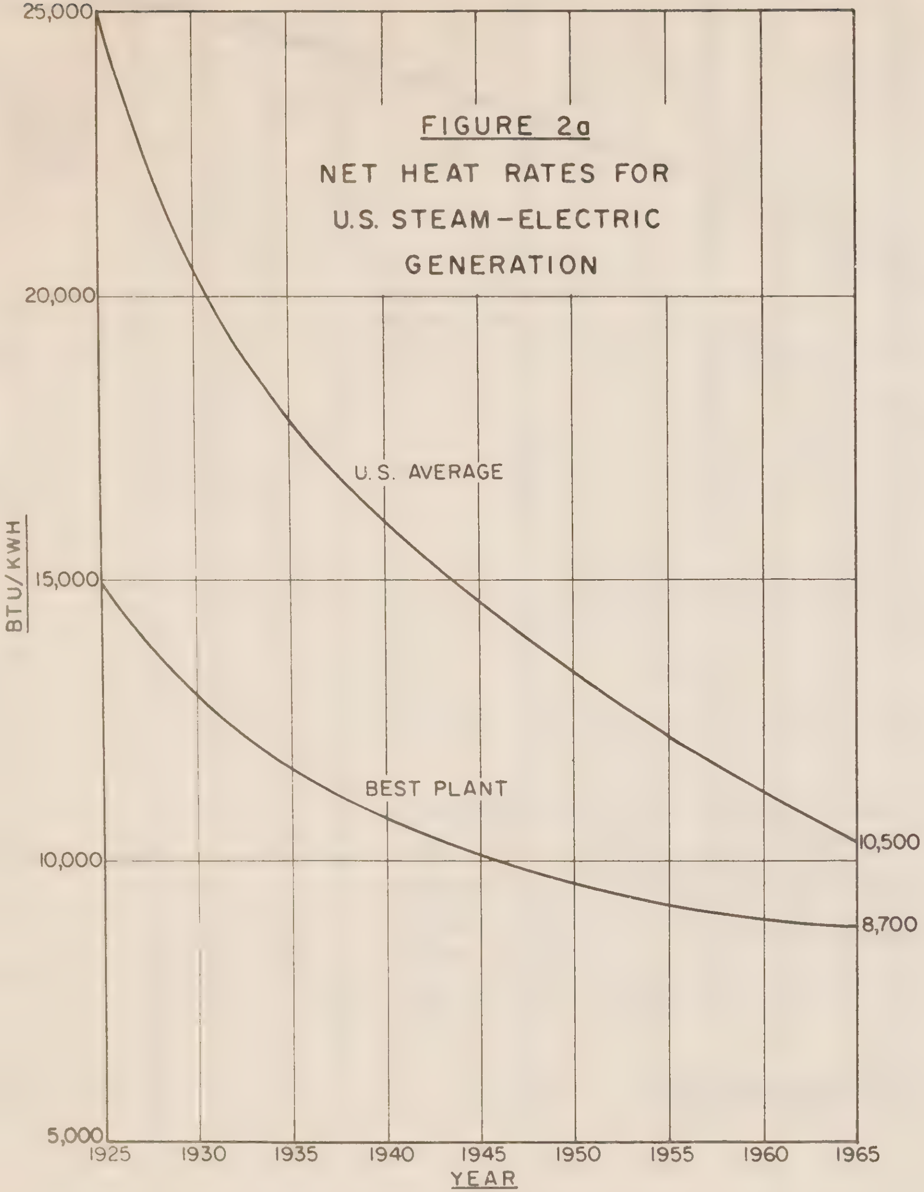
grown the technology has advanced; unit sizes have increased - 1130 Mw units are now under construction; temperatures and pressures have increased - 1100°F and 5000 psi conditions are in use on some units; heat rate improvements have been continuous - average annual heat rates below 8700 BTU per kwh have been attained. These technical advances have brought fossil generation close to a "perfected" state, as evident by the heat rate and capital cost trend curves shown in Figure 2. It is apparent from the levelling-out of these characteristics that no major reduction can be expected in fossil generation energy costs (at a fixed fuel supply cost) without a new technological development such as in magnetohydrodynamics.

The decreasing heat rate trend has resulted in a traditional pattern whereby new fossil units are added as base generation while the assigned positions of the older units move upward in the load duration curve. This pattern is displayed in Figure 3 which shows the annual load duration curves for thirty years on a fossil system expanding at $7\frac{1}{4}\%$ load growth, i.e. doubling every ten years. Assuming a 15% reserve margin, it can be seen that a new unit serves as either base or intermediate generation for about ten years, as peaking generation for about ten years, and as reserve for about ten years. Maintenance schedules cause

FIGURE 2

FOSSIL GENERATION HEAT RATE AND CAPITAL COST TRENDS

(From F.P.C. Statistics and National Power Survey)



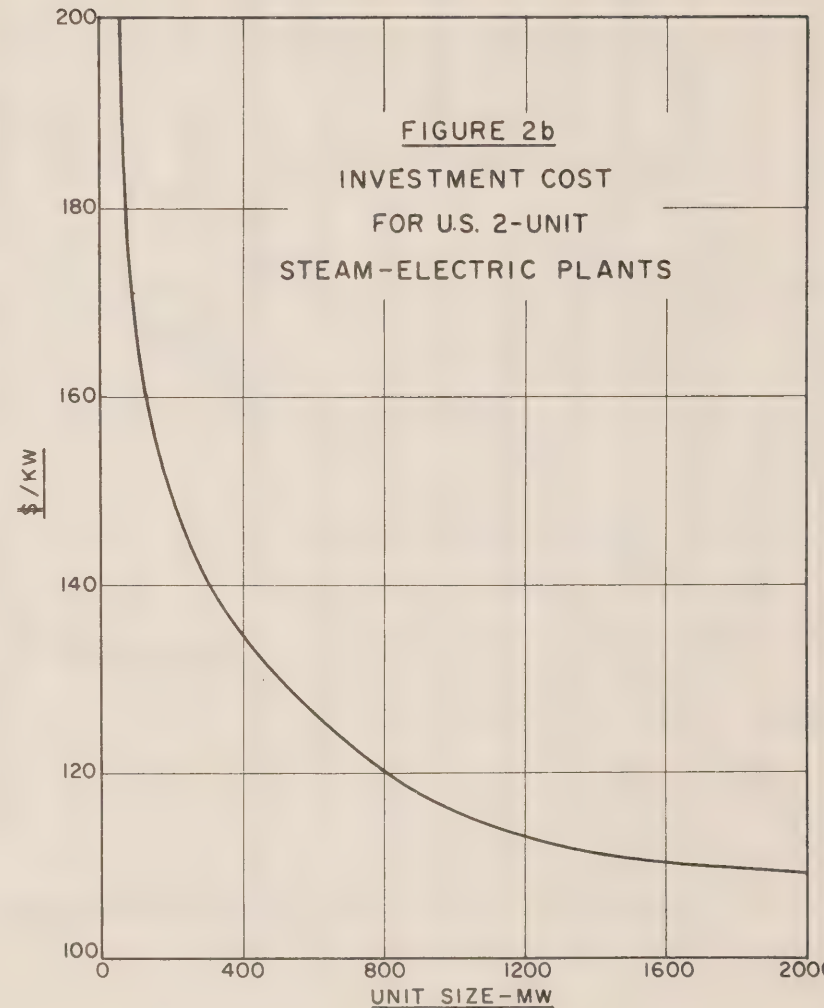
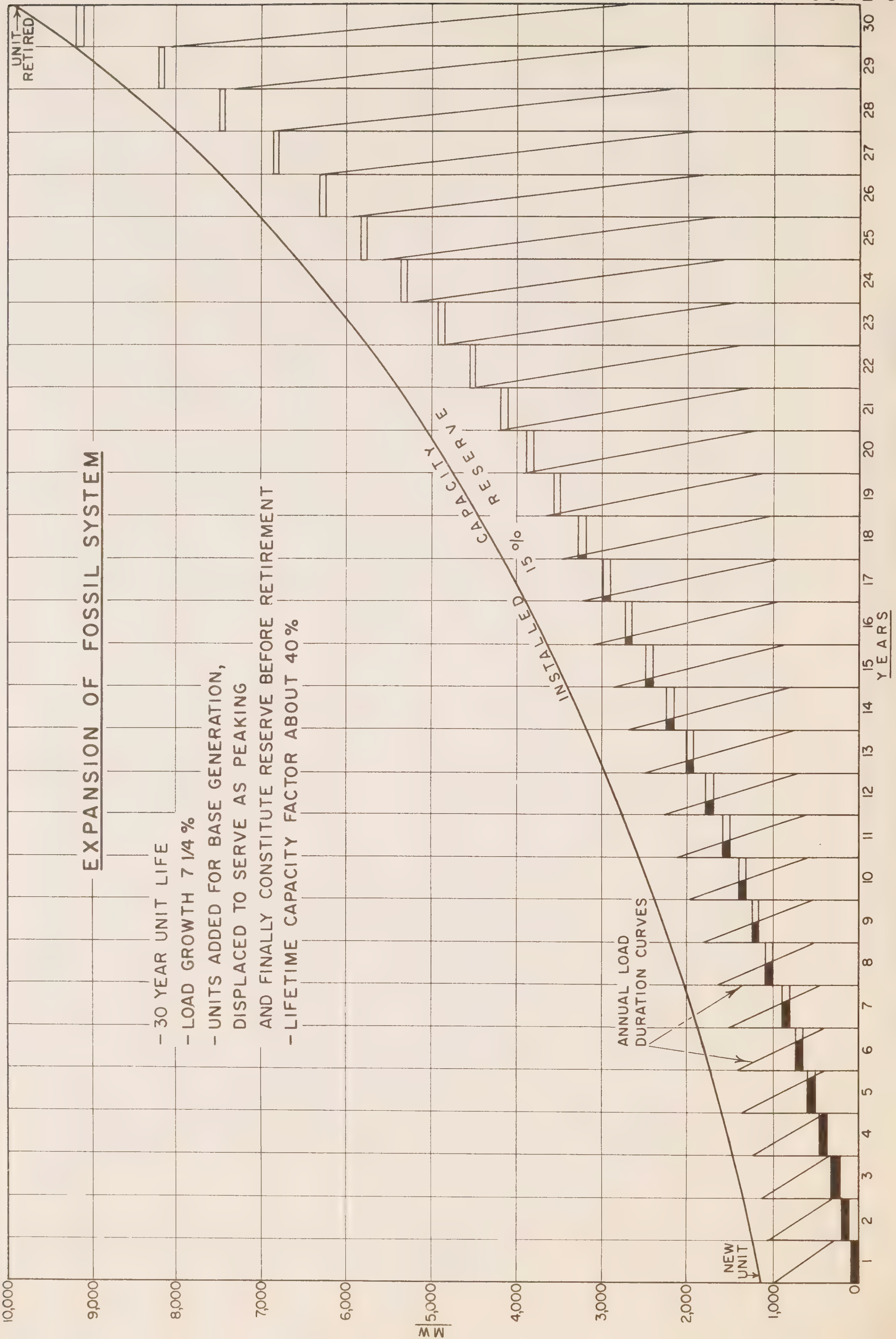


FIGURE 3


EXPANSION OF FOSSIL SYSTEM
- 30 YEAR UNIT LIFE
- LOAD GROWTH 7 1/4 %
- UNITS ADDED FOR BASE GENERATION,
DISPLACED TO SERVE AS PEAKING
AND FINALLY CONSTITUTE RESERVE BEFORE RETIREMENT
- LIFETIME CAPACITY FACTOR ABOUT 40%
INSTALLED 15 % CAPACITY RESERVE
ANNUAL LOAD DURATION CURVES
NEW UNIT
UNIT RETIRED
MW
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
YEARS
1
2
3
4
5
6
7
8
9
10
11
12
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the unit to operate as replacement for a portion of the year, increasing the loading somewhat over that shown. The lifetime capacity factor for a unit on this all-fossil system would be about 40%; other growth rates of course would modify this pattern.

In low-cost fuel areas such as the coal fields of West Virginia and Alberta or the lignite fields of Saskatchewan and South Dakóta fossil generation will continue to serve as a source of low-cost base generation. In high-cost fuel areas nuclear power is being installed as the base generation wherever the large unit sizes that are necessary for economic nuclear power can be introduced. In these high-cost fuel areas nuclear power will gradually relegate fossil generation to the role of intermediate generation. Because of the reduced energy role of fossil generation when combined with nuclear generation, the desirable characteristics for future fossil units as intermediate generation will probably be low capital cost, simplified cycle, fast startup, two-shifting, minimum staff and load-following.

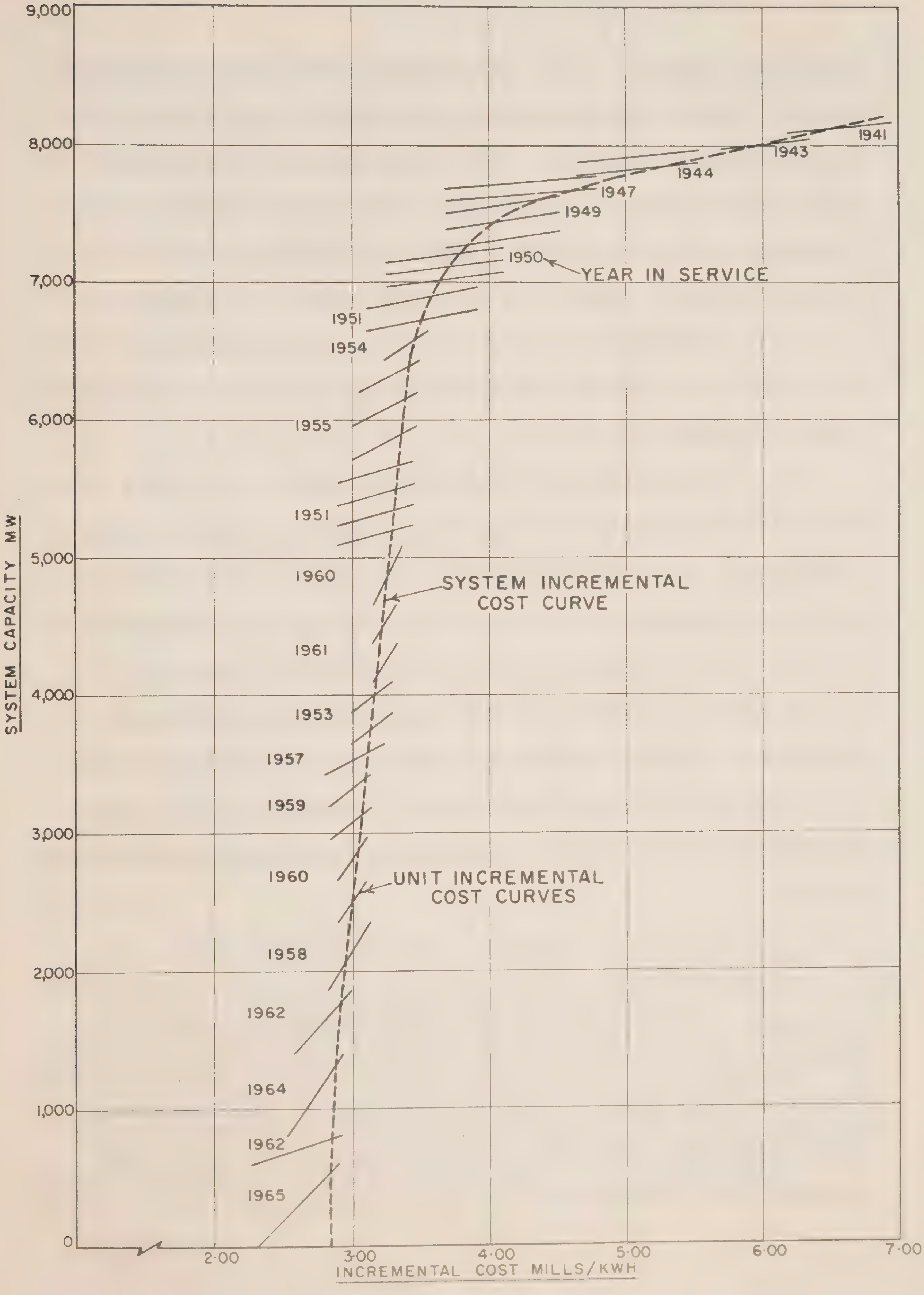
Because of the continuing use of fossil units as intermediate generation and the introduction of pumped storage for peaking, future nuclear units will have a much higher lifetime capacity factor than the 40% lifetime capacity factor associated with units on an all-fossil system.

When used in conjunction with pumped storage the lifetime capacity factor for nuclear generation will approach the nuclear unit availability factor, which may be 85%. The future fossil lifetime capacity factor will decline below 40% because of the change in role of the fossil units. This difference in lifetime capacity factors makes erroneous any spot or lifetime energy cost comparison of fossil and nuclear alternatives unless a computer is used to ascertain the actual lifetime operating patterns.

In the dispatching of fossil generation there are three production costs that have to be considered - startup costs, no-load costs and incremental fuel costs. Once the fossil generation is committed to start (for capacity requirements) the relative loading of units is determined by the comparative incremental fuel costs. Figure 4 shows the development of the system incremental cost curve for a typical fossil system. Each unit on the system has an independent incremental cost curve based on the variation in incremental cost from the minimum load position to the full load position. The system incremental cost curve represents the capacity addition of the various units making up the system in ascending order of individual incremental cost. To obtain minimum system operating costs the system dispatch for a given load involves loading the

FIGURE 4

DEVELOPMENT OF SYSTEM INCREMENTAL COST CURVE FOR FOSSIL SYSTEM



operating units at equal incremental fuel costs and as the system load varies the system incremental cost follows the dotted line on Figure 4. Note that the units installed since 1950 reflect a significant improvement in heat rate compared to earlier units. Assuming that units are retired after 30 years, by 1980 the system incremental cost for this typical fossil system would range from about $2\frac{1}{2}$ mills per kwh to $3\frac{1}{2}$ mills per kwh, a significant overall reduction.

When nuclear capacity is added to a fossil system to exceed the minimum load point the system incremental cost curve will extend to the left of the curve on Figure 4, ranging from 0.5 to 1.5 mills per kwh depending on the type of nuclear power. This distinct reduction in the system incremental cost curve for future systems means that nuclear generation, once installed, will always be loaded before fossil generation, resulting in the high lifetime capacity factor for nuclear generation as mentioned earlier.

4. PUMPED STORAGE

Pumped storage can be developed as part of the generation supply on those systems having economic sites. Pumped storage projects utilize reversible pump-generator hydro units and low-cost off-peak pumping energy to pump storage into a reservoir for later peaking service.

Published prices on projects in the United States range from \$80 per kw to \$135 per kw. Dependent on the relative size of the reservoirs and the pumping capacity, pumped storage projects may operate on a daily, weekly or seasonal cycle. Because of the light load on weekends, it is preferable to employ at least a weekly cycle whereby energy pumped on the weekend, supplemented by pumping on week-nights, provides peak energy for each of the five weekday peaks. With this arrangement the upper reservoir cycles from "full" on Monday morning to "minimum level" by Friday night. To utilize fully the available pumping hours it is desirable that all units at pumped storage projects be combination pump-generator units.

There are three basic types of pumped storage:

1) Pure Pumped Storage - In pure pumped storage an upper reservoir is developed on a mountain, hill or cliff near an existing lake or river. The Taum Sauk project of the Union Electric Company is an example of pure pumped storage.

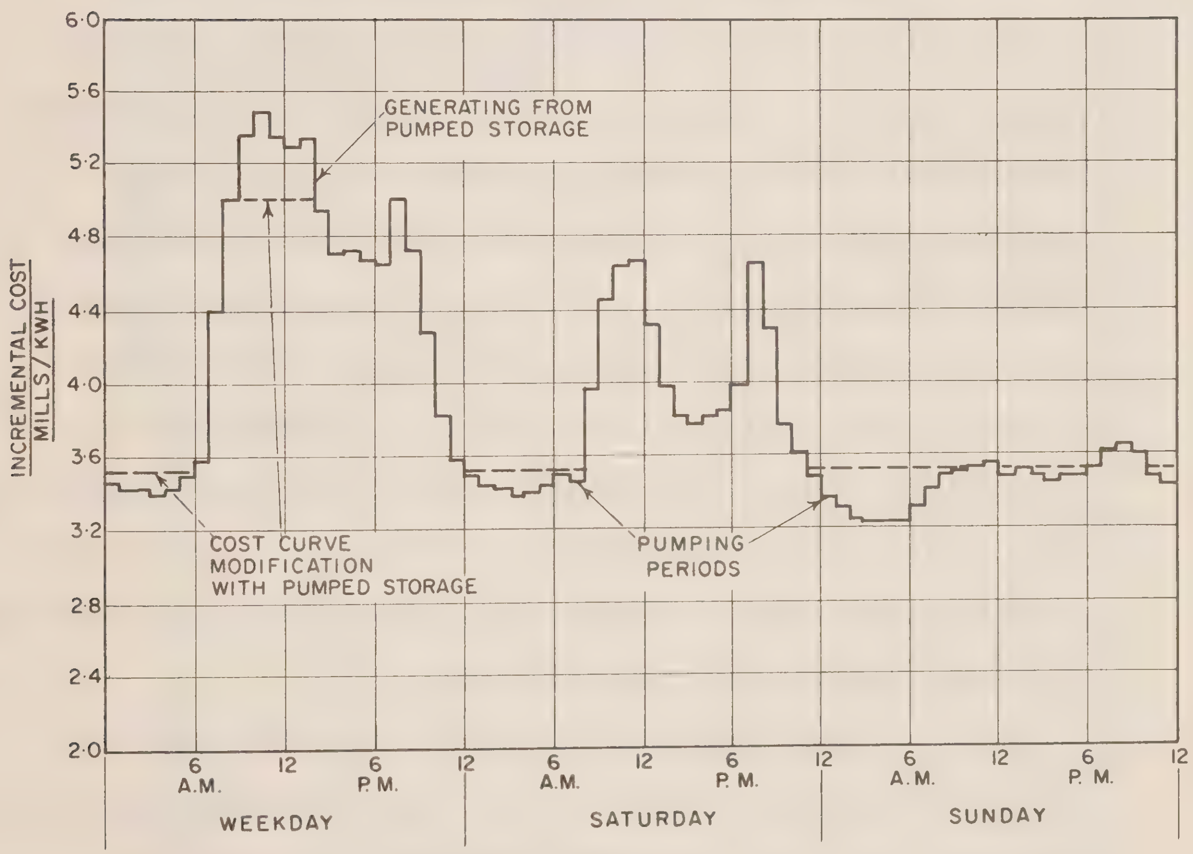
2) River Pumped Storage - Pumped storage can be developed in conjunctinn with conventional hydro by establishing two reservoirs on a river. The lower reservoir has conventional hydro units which regulate the stream flow and serve as a peaking hydro plant. The upper reservoir has pump-generators which cycle water between the two

reservoirs to transfer off-peak energy to the peak period. The American Electric Power Smith Mountain project on the Roanoke River in Virginia is an example of river pumped storage.

3) Redeveloped Pumped Storage - On rivers that have few restrictions on flows and levels it is possible to redevelop conventional hydro plants as pumped storage projects. Pumped storage is particularly adaptable to existing hydro sites where plants are cascaded on a river, thus providing the required upper and lower reservoirs.

The economic advantage of pumped storage results from the slope of the system incremental cost curve as shown in Figure 4. The weekly pattern of system incremental cost variation for such a typical fossil system is shown in Figure 5. The sharp reduction in system cost at night and on Sundays provides a supply of low-cost pumping energy that can be converted to peaking energy, to displace the high cost fossil units in the system incremental cost curve at a saving in operating costs. Note that in this example pumping commences when the system cost drops to about 3.5 mills per kwh; pumping continues at this system cost until the increasing system load causes the system cost to rise above 3.5 mills per kwh.

HOURLY VALUES FOR SYSTEM INCREMENTAL COSTS ON A TYPICAL FOSSIL SYSTEM



The potential savings in operating costs with pumped storage can be illustrated by examining various system incremental cost annual duration curves. Figure 6 shows typical incremental cost curves for the following systems:

a) a fossil system

b) a fossil system with pumped storage

c) a mixed fossil, nuclear, pumped storage system.

In Figure 6a the system incremental cost annual duration curve is shown for the fossil system cost curve displayed in Figure 4. In Figure 6b pumped storage is combined with the fossil generation. The off-peak pumping energy cost is about 3.5 mills per kwh, giving a value of 5 mills per kwh for the energy in the storage reservoir, based on 70% cycle efficiency. This pumped storage energy is then dispatched as a thermal source, displacing the high cost fossil units having an incremental cost above 5 mills per kwh with a saving in incremental costs as indicated in Figure 6b (there may also be a saving in fossil startup and no-load costs).

When the fossil system is expanded with the addition of nuclear generation in excess of the system base load, off-peak nuclear energy becomes the source for pumping energy as shown in Figure 6c. Assuming this pumping energy is from the present designs of heavy water

FIGURE 6

SYSTEM INCREMENTAL COST ANNUAL DURATION CURVES

FIGURE 6 a

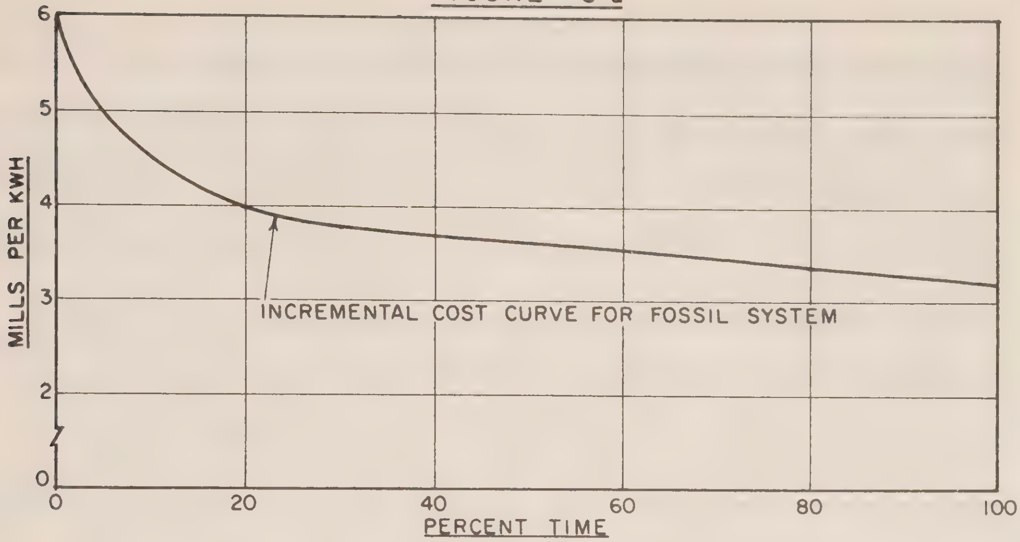


FIGURE 6 b

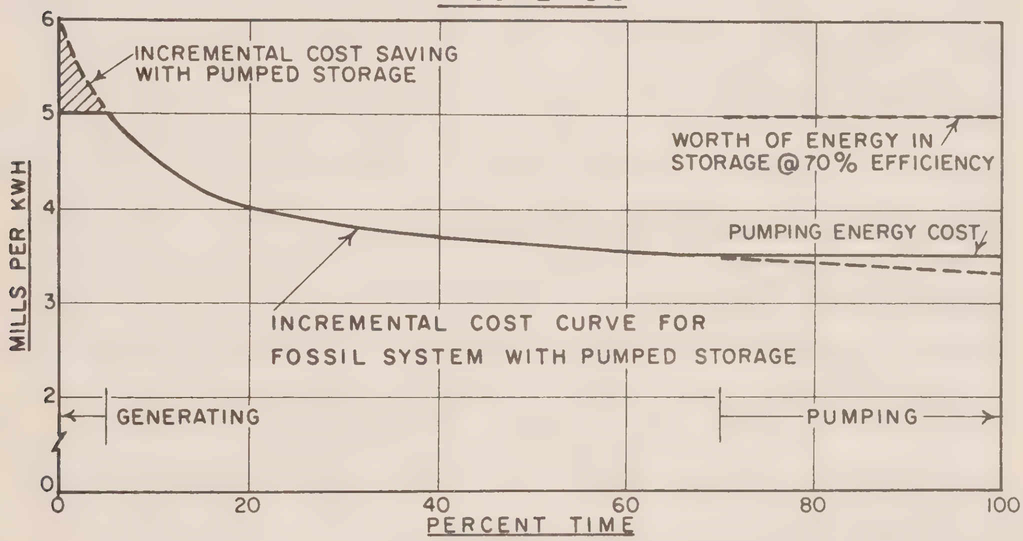
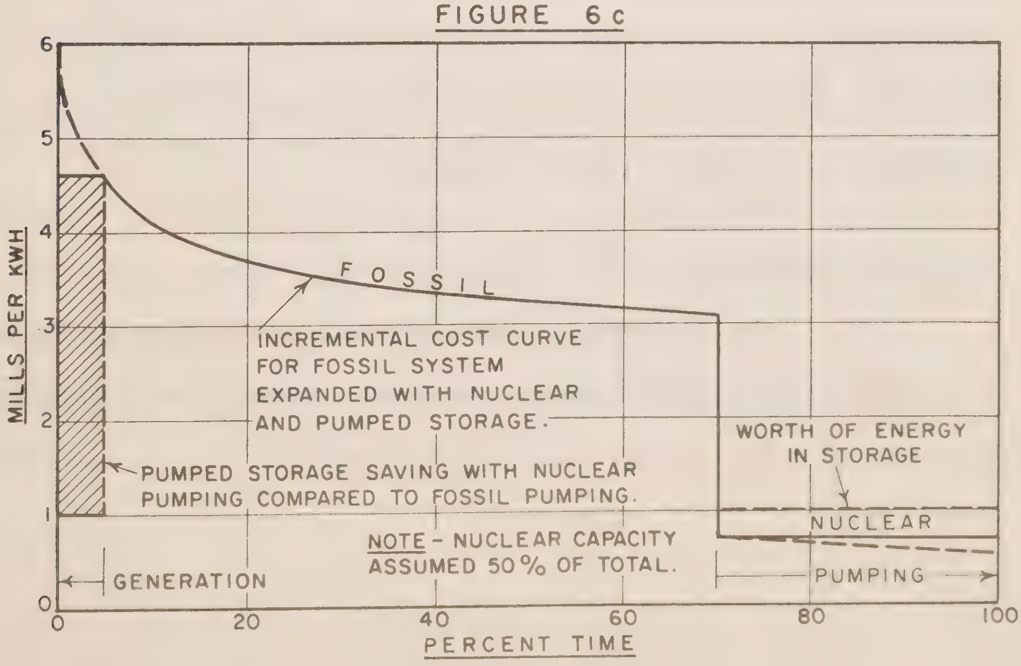


FIGURE 6 c



reactors the incremental cost would be about 0.7 mills per kwh, resulting in a worth of about 1 mill per kwh for the energy in the pumped storage reservoir. This pumped storage energy will always be cheaper than any incremental fuel costs for fossil. The nuclear-supplied pumped storage would be dispatched for peaking based on the available energy, much like a peaking hydro plant, whereas in the case of a fossil-supplied pumped storage the alternative incremental generation cost would be the dispatch criterion. It was shown earlier that nuclear generation, once installed, will always be operated to full capacity before fossil generation; it is also true that nuclear-supplied pumped storage, once installed, will always operate in preference to any fossil generation, to the extent that pumped storage energy is available.

The substantial reduction in operating costs for pumped storage when nuclear-supplied as compared to fossil-supplied is apparent in Figure 6c. It is clear that the introduction of nuclear power with its inherent low fueling cost can amplify the advantage of pumped storage by providing a source of cheap pumping energy.

5. GAS TURBINES

As a result of the rapid development in the air transportation field a new type of generation is available.

Aircraft jet engines have been combined with gas turbines and conventional generators to provide compact units having a nominal rating of 20 Mw per unit, available in single or multiple arrangements. The comparatively-low capital cost of about $100 per kilowatt makes these units ideal for reserve capacity in cases where additional reserve must be provided. Heat rates of 12,000 BTU per kwh have been attained with these units but the fuel must be high-grade liquid or gas and the fuel cost is therefore high, usually restricting operation to less than 5% annual capacity factor. The fast startup time of about two minutes makes the gas turbine ideal for "spinning reserve" applications and as station startup units for much larger thermal or nuclear units in the event of system shutdown. Unforeseen load increases or major generation schedule delays can be overcome with the gas turbine because of the short installation time - one year or less.

If entirely new power systems were being designed the gas turbine could probably compete successfully throughout the capacity reserve section of the generation system, however, because power system expansions are an evolutionary process and as such have to include the utilization of existing equipment, such a straightforward selection is not possible. On most existing systems there are possibilities

for either capacity expansions at conventional hydro plants or displacement of older fossil units to standby reserve, thus satisfying the reserve requirements for some time with minimum expenditure of new capital.

Because of this availability of inherited reserve capacity on most systems, gas turbine applications in the immediate future will probably be for special purposes such as "spinning reserve" or "black startup". Ultimately gas turbines may provide a large portion of the system reserve.

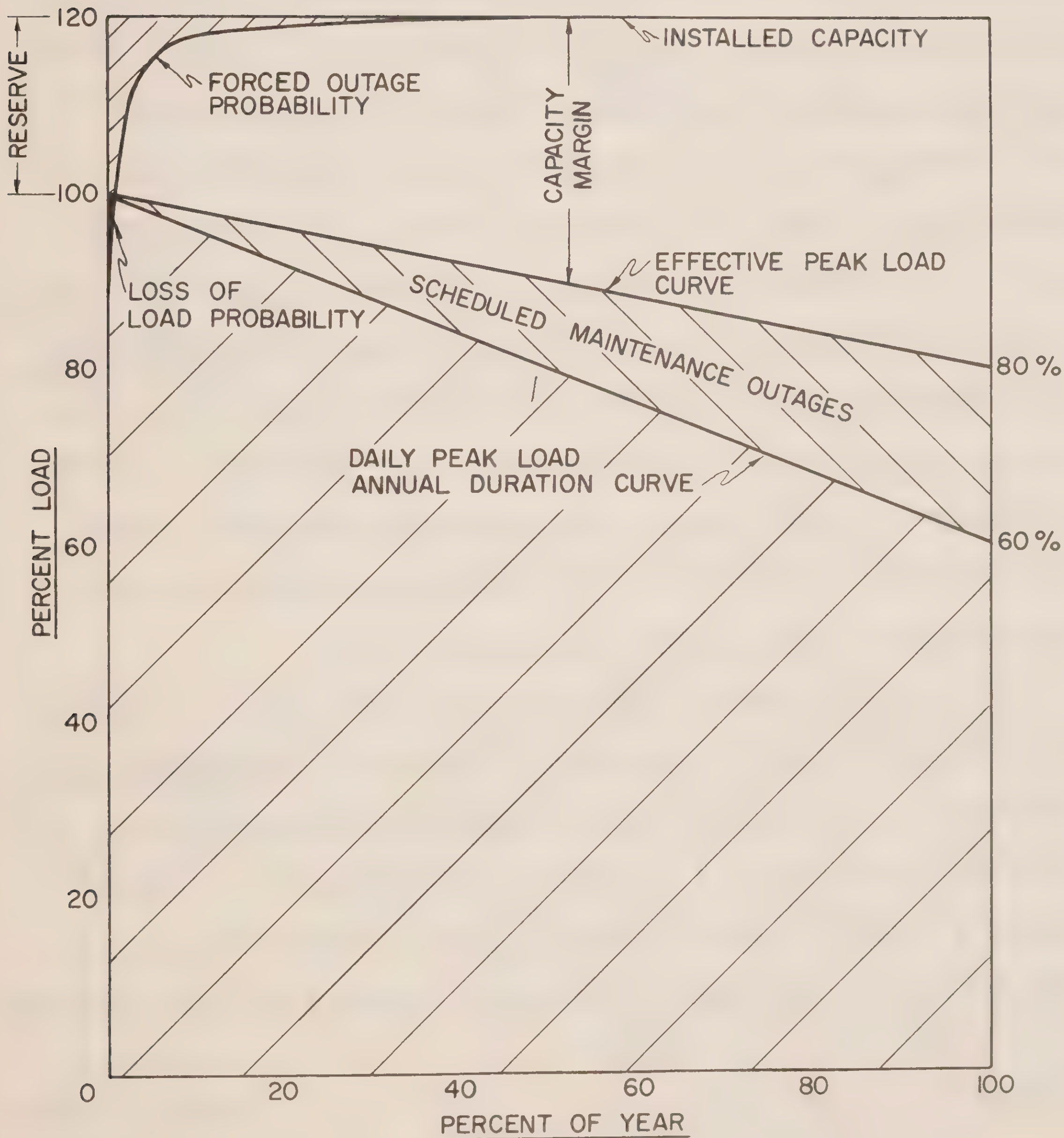
6. RESERVE CAPACITY

The reserve requirement on future systems is important because the cost of this system reserve must be distributed throughout the system generation cost.

On any power system a capacity margin must be provided to cover contingencies such as generation forced outages; thermal capacity reductions due to ambient air or cooling water limitations; hydro capacity reductions due to low flows, adverse wind or ice conditions; allowances for scheduled maintenance outages and possibly the forced outages of some transmission lines. The capacity reductions due to adverse plant conditions have a definite megawatt value, therefore an appropriate allowance can be made. The maintenance reserve, when required, is a specific allowance.

FIGURE 7

DEVELOPMENT OF
LOSS OF LOAD PROBABILITY



The largest reserve requirement on most systems is the generation forced outage allowance.

Within recent years many utilities have adopted the "loss-of-load" method of analyzing the forced outage reserve requirement, by determining the reserve necessary to prevent loss of load more frequently than a given target reliability, usually once in 5 to 10 years. Figure 7 shows the development of the loss-of-load probability as the combination of the capacity forced outage probability curve and the peak load duration curve. Historical hydro unit forced outage rates have been about 0.5%, fossil unit rates have been about 3.0% and recent experience indicates that future nuclear unit forced outage rates will possibly be no higher than for fossil units. The effects of system parameters on the forced outage reserve requirement were studied using a "loss-of-load" computer program and the results are shown in Figure 8.

Figure 8a shows the effect of number of units for a hydro system; with only 10 units an 11% reserve is required to attain the 5 to 10 year target reliability; with 1000 units only a 2% reserve is required; a nominal reserve value for hydro systems is 5%. Figure 8b shows the effect of unit size relative to system size for a thermal

FORCED OUTAGE RESERVE REQUIREMENTS

FIGURE 8

FIGURE 8a

EFFECT OF NUMBER OF IDENTICAL UNITS ON HYDRO SYSTEMS

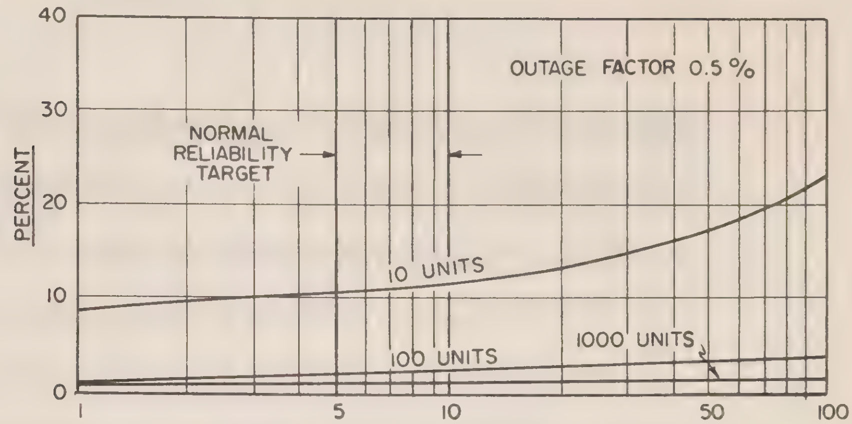


FIGURE 8 b

EFFECT OF UNIT SIZES ON LARGE THERMAL SYSTEMS

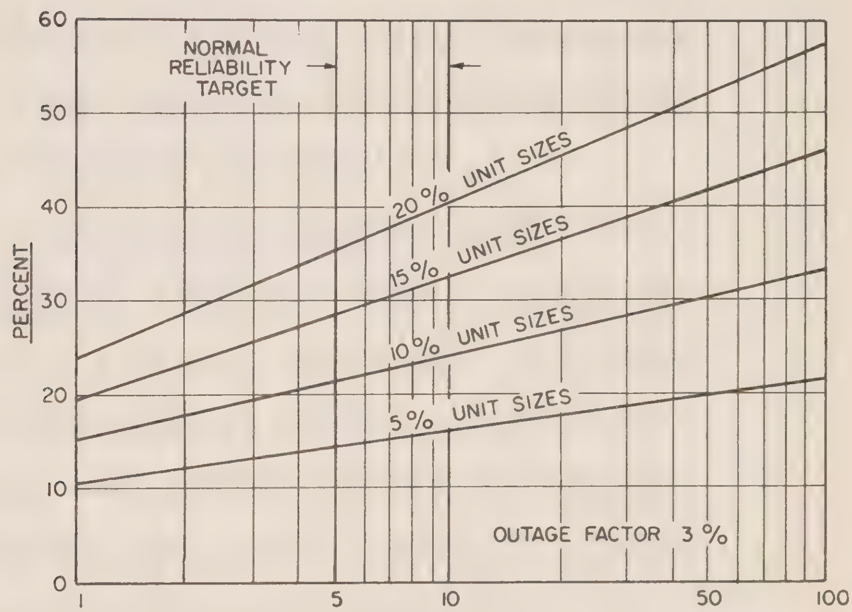


FIGURE 8c

EFFECT OF CHANGE IN OUTAGE PROBABILITY FOR A 10,000 MW THERMAL SYSTEM

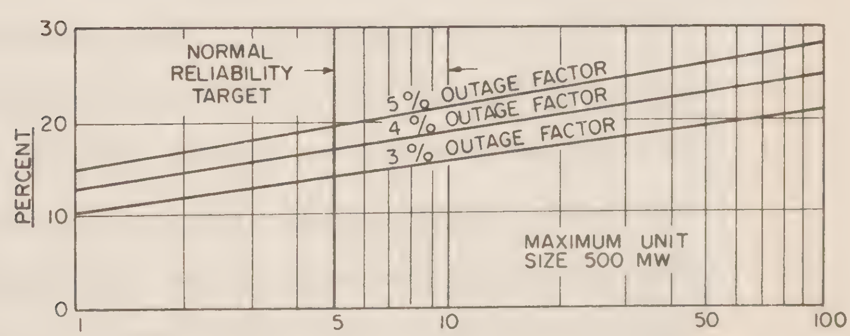
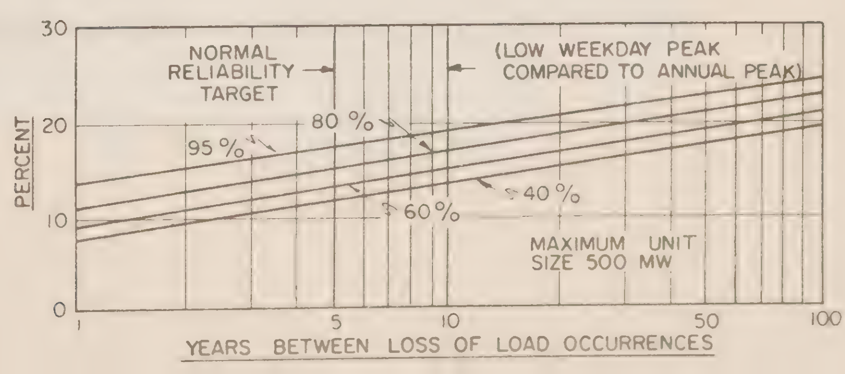


FIGURE 8d

EFFECT OF CHANGE IN LOAD SHAPE FOR A 10,000 MW THERMAL SYSTEM



system; the reserve requirements vary from 15% with 5% unit sizes to 38% with 20% unit sizes; a nominal reserve value for thermal systems is 15%.

Figure 8c shows the effect of unit reliability; thermal unit forced outage rates of 3%, 4% and 5% have been tested for a 10,000 Mw thermal system; the reserve requirement varies from 15% at the 3% forced outage rate to 20% at the 5% forced outage rate.

In Figure 8d the effect of the load shape on the reserve requirement is illustrated. On northern systems the minimum weekday peak load is about 60% of the annual peak load. Systems with large air conditioning loads tend to have a smaller differential between the annual peak and the minimum weekday load. The load shape has about a 5% overall effect upon the reserve requirement.

The introduction of nuclear power will probably increase forced outage reserve requirements to 20% or more, particularly if large unit sizes are accepted, thereafter the system growth and the effect of further interconnections could result in a gradual reduction of forced outage reserves - the 1964 F.P.C. National Power Survey estimated the 1980 generation forced outage reserve requirement for the entire United States as being 8.1%.

The introduction of pumped storage in association with nuclear generating units will eventually necessitate additional maintenance reserve, because the nuclear units will be loaded as continuously as possible, and reserve nuclear capacity will be required to maintain this supply of base generation. The required maintenance reserve might be 7%, which, when combined with the ultimate forced outage reserve requirement of about 10%, would maintain the overall reserve requirement in the 15% to 20% range.

7. OPTIMUM GENERATION MIX FOR A NEW SYSTEM

Generation planning consists of analyzing present generation alternatives to determine the plan that results in minimum discounted future operating and capital costs. Experience has shown that a common long-term target system must be used to avoid confusing the effect of immediate and future decisions. To serve as a guide to the future generation trends a graphical method can be used to determine the optimum economic mix of the various available generation sources.

Fixed charge rates must be established for the different types of generation, for example, for utilities in the government sector, representative values are as follows:

Nuclear and Fossil

Interest on investment	-	6.50%
Depreciation (30 years S.F.)	-	1.16%
Interim replacements	-	0.34%
Total	-	8.00%

Gas Turbine

Interest on investment	-	6.50%
Depreciation (25 years S.F.)	-	1.70%
Interim replacements	-	0.30%
Total	-	8.50%

Pumped Storage

Interest on Investment	-	6.50%
Depreciation (50 years S.F.)	-	0.29%
Interim Replacements	-	0.21%
Total	-	7.00%

For purposes of illustration it is assumed that a situation has arisen permitting the construction of a new power system, such as in a fast-developing country, without the constraints of an existing system.

Based on the acceptable unit sizes, it is assumed alternative generation is available with the following characteristics:

Nuclear

- heavy water reactors at $300 per kw (300 Mw Size).
- annual operating and maintenance costs, including heavy water makeup, of $5.0 per kw.
- fueling cost of 0.7 mills per kwh, including a plutonium credit.

- unit availability of about 87% (therefore the capital cost should be increased 15% to allow for maintenance reserve as base generation).

Fossil

- oil-fired fossil at $150 per kw.
- fuel is residual oil at 35¢ per million BTU.
- average annual heat rate 9200 BTU per kwh.
- annual operating and maintenance costs (except fuel) of $2.5 per kw.

Gas Turbine

- capital cost $100 per kw.
- fuel is light oil at 70¢ per million BTU.
- average annual heat rate 12,500 BTU per kwh.
- annual operating and maintenance costs (except fuel) of $1.0 per kw.

Pumped Storage

- capital cost $150 per kw.
- cycle efficiency 70%.
- the output energy cost is 1.0 mills per kwh based on 0.7 mills per kwh pumping energy cost.
- annual operating and maintenance costs $0.5 per kw.
- large seasonal storage assumed, based on river-type pumped storage, to give maximum cycle flexibility.

These four different types of generation have a wide variation in the ratio of capital costs to operating costs. It is this variation that results in each generation

type being most suited to a particular section of the load curve. This can be seen by examining the following table of total annual costs at various capacity factors.

Per Kilowatt Total Annual Costs

Capacity Factor	100%	80%	60%	40%	20%	0%
Nuclear at $300/kw						
- fixed charges	$27.6	$27.6	$27.6	$27.6	-	-
- O & M	$ 5.0	$ 5.0	$ 5.0	$ 5.0	-	-
- fuel	$ 6.1	$ 4.9	$ 3.7	$ 2.5	-	-
Total	$38.7 *	$37.5 *	$36.3	$35.1	-	-
Fossil at $150/kw						
- fixed charges	$12.0	$12.0	$12.0	$12.0	$12.0	$12.0
- O & M	$ 2.5	$ 2.5	$ 2.5	$ 2.5	$ 2.5	$ 2.5
- fuel	$28.2	$22.6	$16.9	$11.3	$ 5.6	$ 0.0
Total	$42.7	$37.1	$31.4 *	$25.8 *	$20.1	$14.5
Pumped Storage at $150/kw						
- fixed charges	-	-	-	$10.5	$10.5	$10.5
- O & M	-	-	-	$ 0.5	$ 0.5	$ 0.5
- fuel	-	-	-	$ 3.5	$ 1.8	$ 0.0
Total	-	-	-	$14.5 **	$12.8 *	$11.0
Gas Turbine at $100/kw						
- fixed charges	-	-	-	$ 8.5	$ 8.5	$ 8.5
- O & M	-	-	-	$ 1.0	$ 1.0	$ 1.0
- fuel	-	-	-	$30.6	$15.3	$ 0.0
Total	-	-	-	$40.1	$24.8	$ 9.5 *

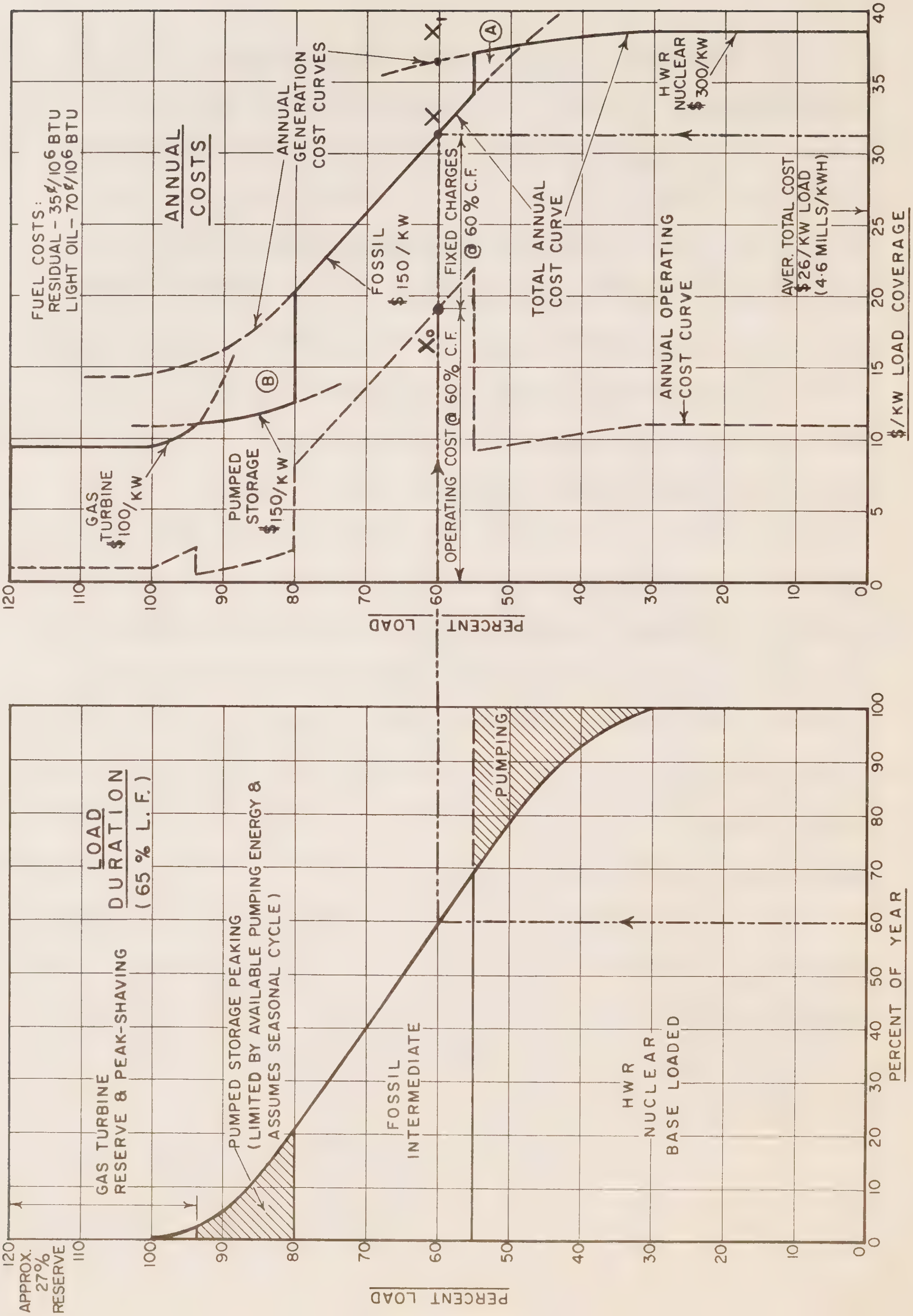
* indicates lowest cost supply at the particular capacity factor.

** limited to lower capacity factor by available pumping energy.

The total annual costs for the "new" system have been developed in detail to permit plotting the annual generation cost curves associated with the annual load duration curve, as shown in Figure 9. Note that the costs are plotted as "$/kw load coverage" and represent the annual cost of supplying a specific kilowatt in the load curve, obtained at any point by adding the operating cost at that point to the fixed charges per kilowatt. This is done for each type of generation. For example, point X_o is the operating cost of supplying a kilowatt from fossil at 60% capacity factor, point X is the total cost of supplying a kilowatt from fossil at that point, and point X_1 is the total cost for nuclear. Based on the asumptions made, the minimum cost system can be selected by assigning the generation types to sections of the load curve to minimize the overall cost. Note that nuclear is installed beyond the fossil cost curve, incurring a penalty at "A", in order to obtain adequate pumping energy to permit the larger saving at "B", relative to the fossil and gas turbine cost curves. In the analysis the cost of pumping has been included in the pumped storage operating and total annual cost curves. The system operating cost curve shows the combined O & M and fuel cost for each kilowatt of the load curve.

FIGURE 9

GENERATION MIX - NEW SYSTEM



NOTE - @ 60% ANNUAL CAPACITY FACTOR THE FOSSIL ANNUAL COST IS $31.4/KW LOAD COVERAGE, PERMITTING PLOTTING OF POINT X.

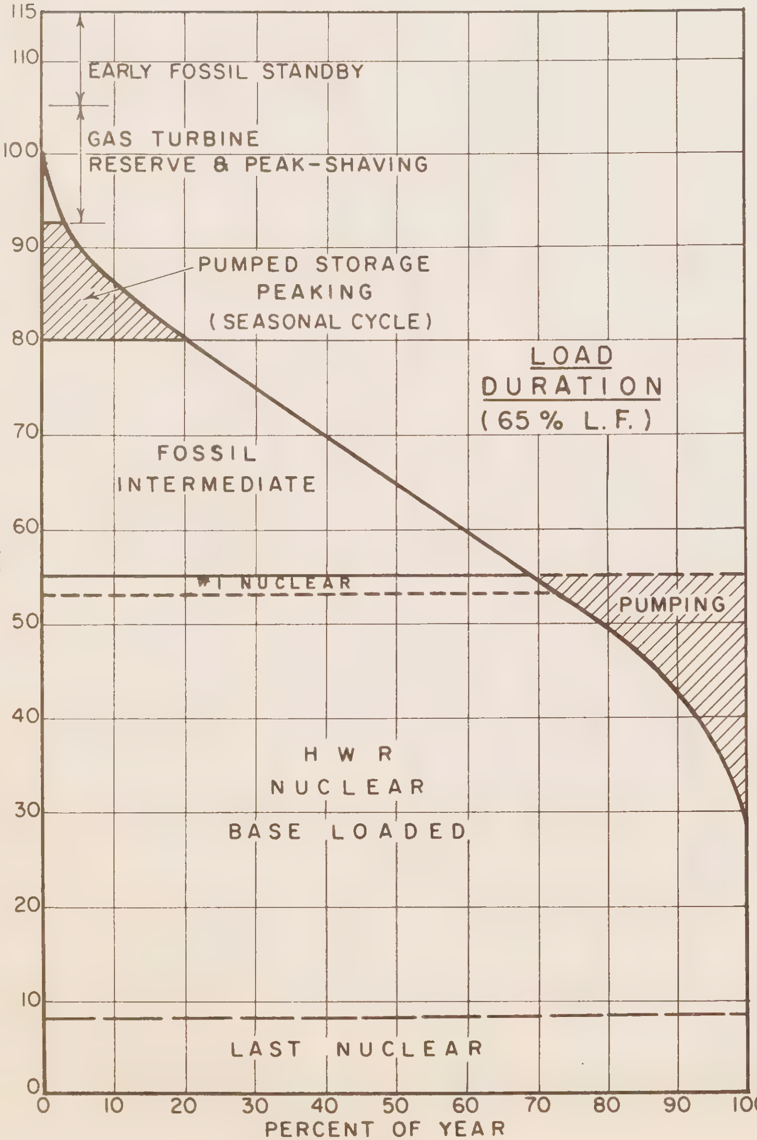
In this particular case 20% forced outage reserve has been assumed and extra nuclear capacity was added for maintenance, as mentioned under "Reserve Capacity", giving a total reserve of 27%. Note that the average cost of supplying a kilowatt of load, including the reserve cost, is about $26. Based on the assumed load factor of 65% the average generation energy cost is therefore 4.6 mills per kwh. For the hypothetical situation assumed this analysis indicates that the generation mix in a new system would be about 50% heavy water nuclear, 20% fossil, 10% pumped storage and 20% gas turbine. The impact of later system additions will change this mix somewhat as will be seen in the next section, however, the analysis confirms that the varying ratios of capital costs to operating costs results in each type of generation being most appropriate for a specific section of the system load curve.

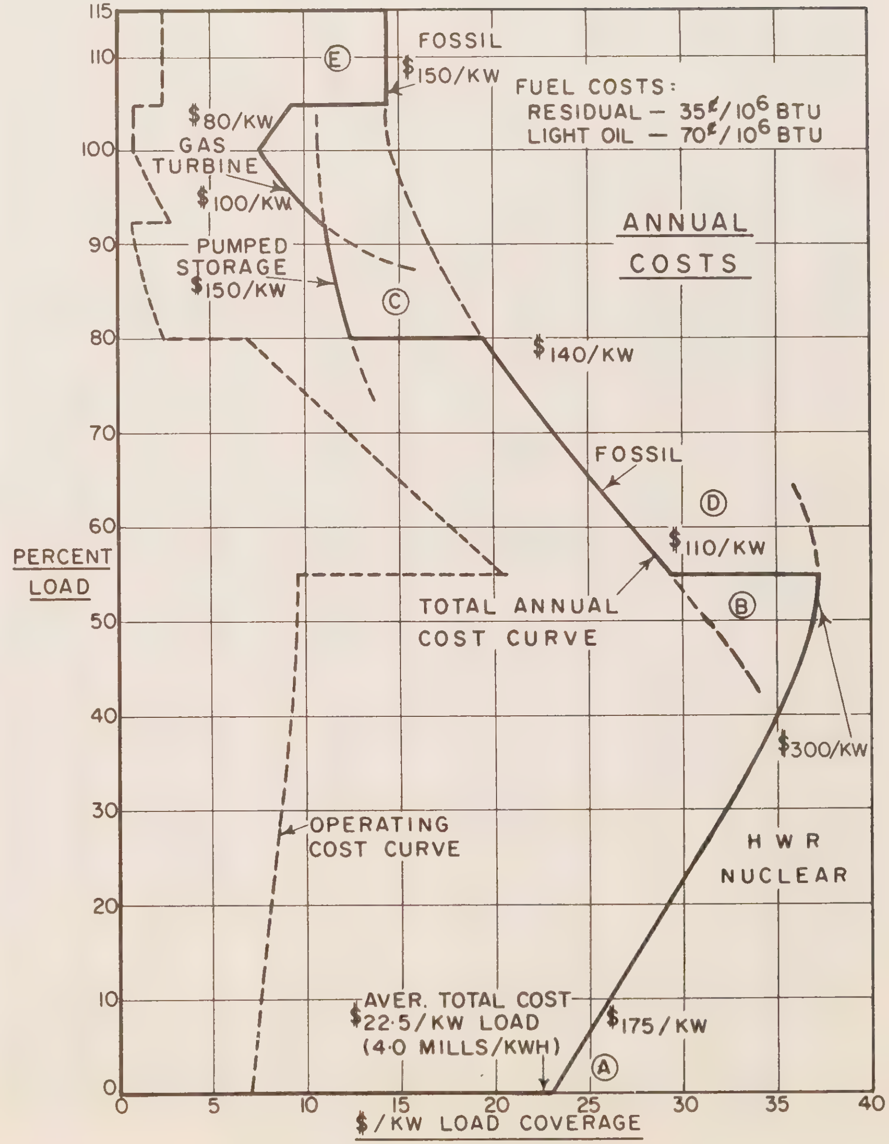
8. GENERATION MIX WITH EXPANDING SYSTEM

In generation planning past decisions and future possible changes in circumstances must be considered in making the next choice in generation alternatives. To show the effect of this continuing evaluation the 'new' system of the previous section has been expanded using the graphical approach. The revised load duration and annual cost curves are shown in Figure 10.

FIGURE 10

GENERATION MIX – EXPANDING SYSTEM





On an expanding system the introduction of larger unit sizes and technical advances would result in economies with succeeding stages of generation. For the advanced stage the following costs are assumed to be representative of a system able to absorb generating unit sizes of about 1000 Mw:

<u>Nuclear</u>

- heavy water reactors at $175 per kw (1000 Mw size)
- annual O & M costs $3.0 per kw
- fueling cost 0.5 mills per kwh (after Pu credit)
- unit availability 87%

<u>Fossil</u>

- oil-fired at $110 per kw
- average annual heat rate 8900 BTU per kwh
- fuel cost 35¢ per million BTU
- annual O & M costs $1.5 per kw

<u>Pumped Storage</u>

- capital cost $150 per kw
- annual O & M costs $0.5 per kw
- cycle efficiency 70%
- pumping energy cost 0.7 mills per kwh (early HWR)

<u>Gas Turbine</u>

- capital cost $80 per kw
- annual O & M costs $1.0 per kw
- average annual heat rate 11,500 BTU per kwh

The economic generation mix developed in Figure 10 is 50% nuclear, 30% fossil, 10% pumped storage and 10% gas turbine. The gas turbine installation is less than for the previous case because the older fossil units are available to use as standby reserve as mentioned in the section on

"Gas Turbines". Note that within the section of the load curve occupied by each generation type the new units enter at the bottom of the band and displace the older units upwards, because later units of each type usually have lower operating costs.

The capital cost reduction of later nuclear units permits a saving at "A" compared to the original nuclear generation costs. Adding extra nuclear generation beyond the improved fossil cost curve results in a cost penalty at "B", which is offset by the combined savings at "A" and the savings with pumped storage at "C" (made possible because the pumping energy is available from the extra nuclear installation). As the fossil generation is expanded a saving is made at "D", relative to the original fossil cost curve, and to attain this saving the early fossil units are relegated to standby reserve. Using the early fossil units as standby reserve represents a penalty at "E" compared to the cost of additional gas turbine reserve, but using the older fossil as reserve makes possible the introduction of the more economic later fossil units with a large saving as mentioned above.

Although the optimizing of the band widths of each type of generation requires the use of a computer this graphical approach permits an approximate assessment

of the relative positions of the different types of generation in the load duration curve on an expanding system.

9. HWR NUCLEAR WITH PUMPED STORAGE

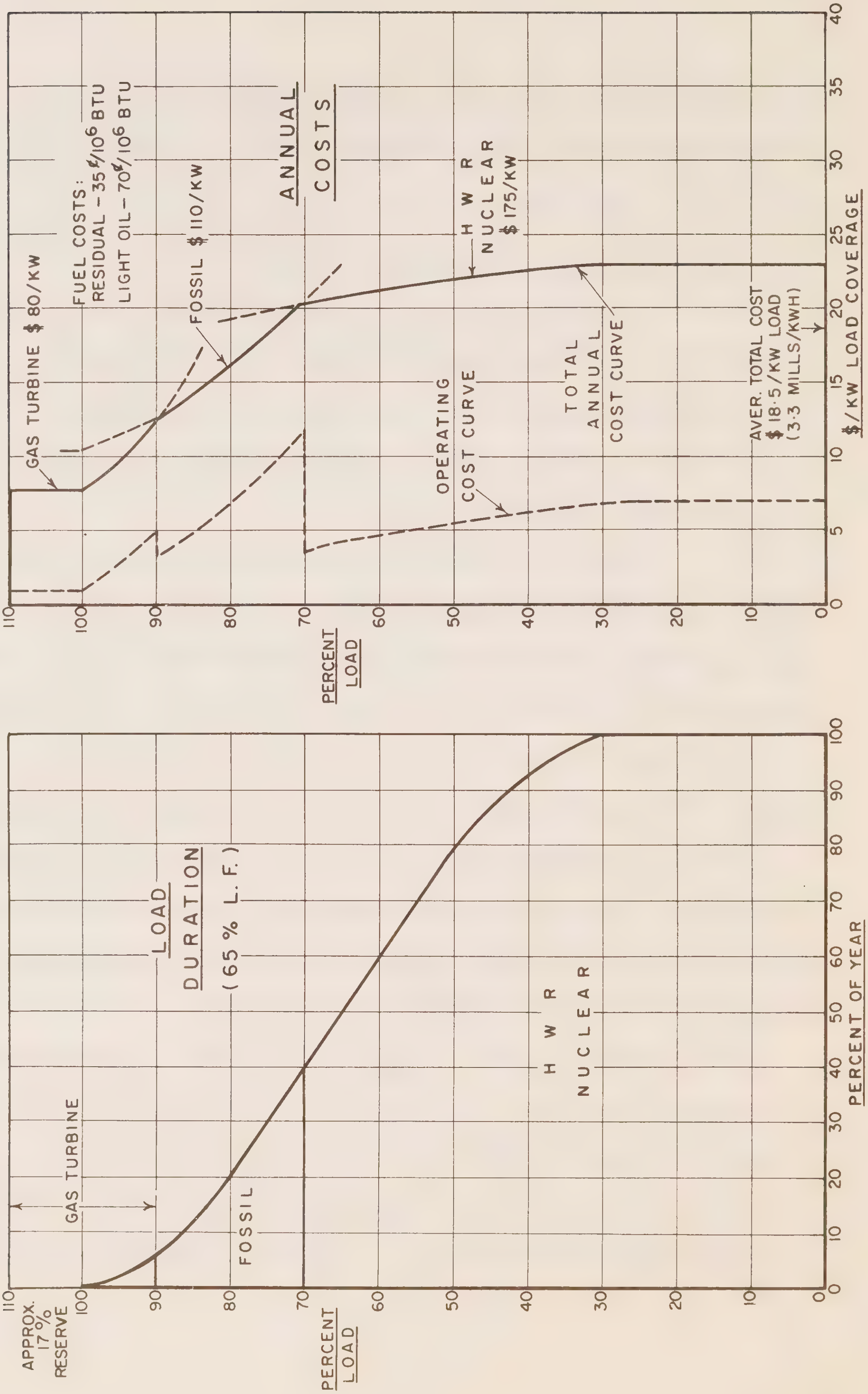
As was pointed out earlier, pumped storage requires a source of low-cost pumping energy to be economic. The heavy water reactor with a potential fueling cost as low as 0.5 mills per kwh after plutonium credit is naturally complementary to pumped storage.

Without pumped storage, when heavy water reactors are installed on any power system in such an amount that the minimum load point is exceeded economy energy transfers to neighbouring systems will occur, because the HWR fueling cost is lower than the fueling cost for other reactor types or fossil units. If the normal "split-the-difference" rule on fuel savings were applied, neighbouring systems would be sharing the benefit which results from the low fueling cost without sharing in the larger capital investment required for the HWR units.

The effect of pumped storage on an HWR system can be shown by examining the generation mixes with and without pumped storage. Figure 11 shows the annual cost analysis for a future system based on the alternatives of $175 per kw HWR nuclear, $110 per kw fossil, and $80 per kw gas turbine.

FIGURE 11

GENERATION MIX – FUTURE HWR SYSTEM
WITH NO PUMPED STORAGE



The detailed characteristics are similar to those used in the preceding section. The resulting generation mix in Figure 11 is approximately 65% HWR nuclear and the remaining 35% is split between fossil generation and gas turbines. Note that the average system total annual cost is $18.5 per kw load or 3.3 mills per kwh.

If we assume that pumped storage is available at $150 per kw the generation mix changes to that shown in Figure 12. Note that the pumped storage can replace the fossil generation permitting a total annual cost saving as shown by area "A", relative to the HWR system without pumped storage. The generation mix is approximately 65% HWR nuclear and the remaining 35% is split between gas turbines and pumped storage. The average system total annual cost has been reduced to $17.5 per kw load or 3.1 mills per kwh.

If we now assume that pumped storage is available at $90 per kw the generation mix changes to that shown in Figure 13. The pumped storage can replace the gas turbines as well as the fossil generation at a saving "A", relative to the original HWR system without pumped storage. The generation mix is now approximately 65% HWR nuclear and 35% pumped storage. The average system annual cost is $17.5 per kw or 2.9 mills per kwh.

FIGURE 12

GENERATION MIX — FUTURE HWR SYSTEM
WITH $150/KW PUMPED STORAGE

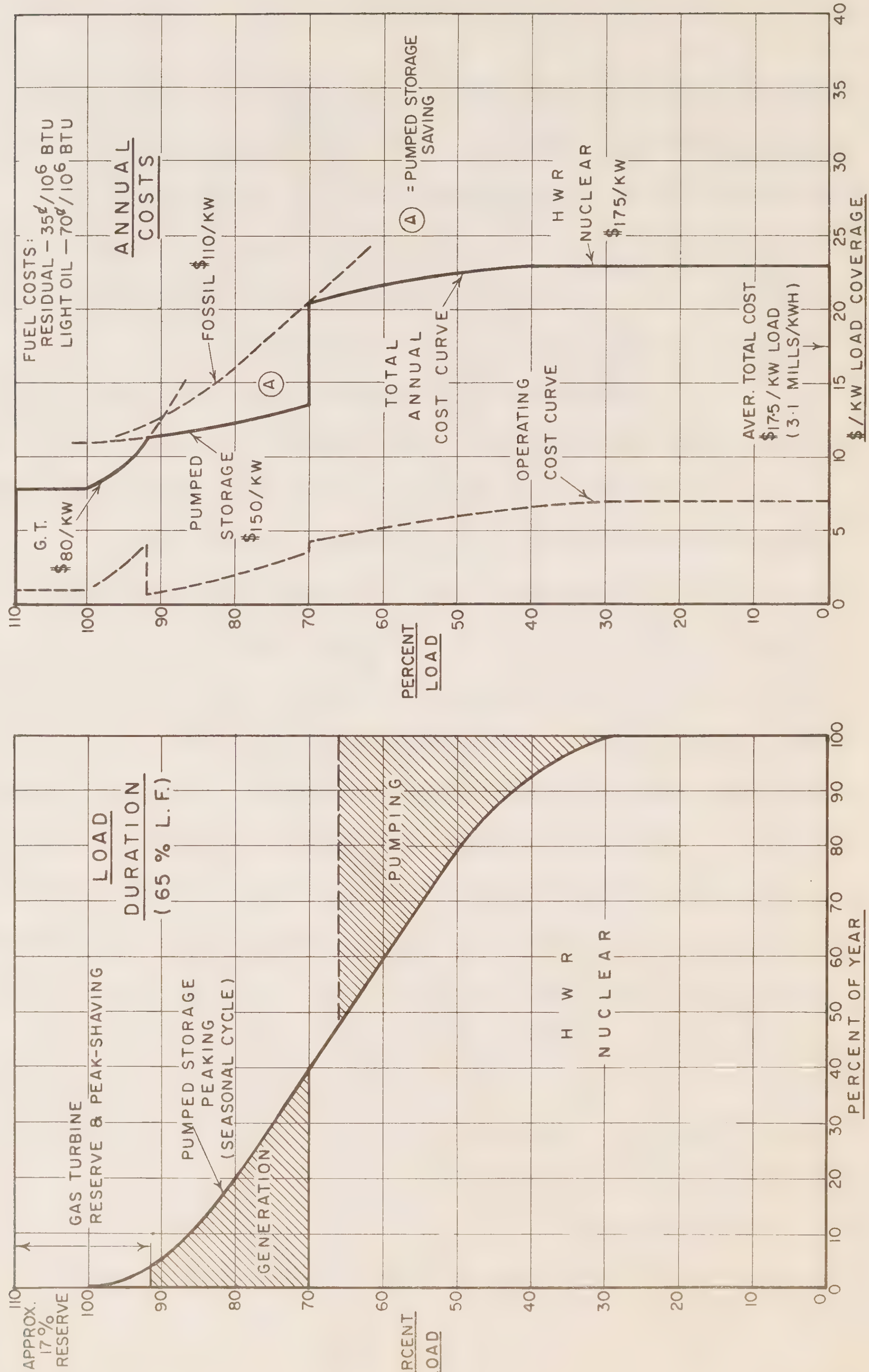
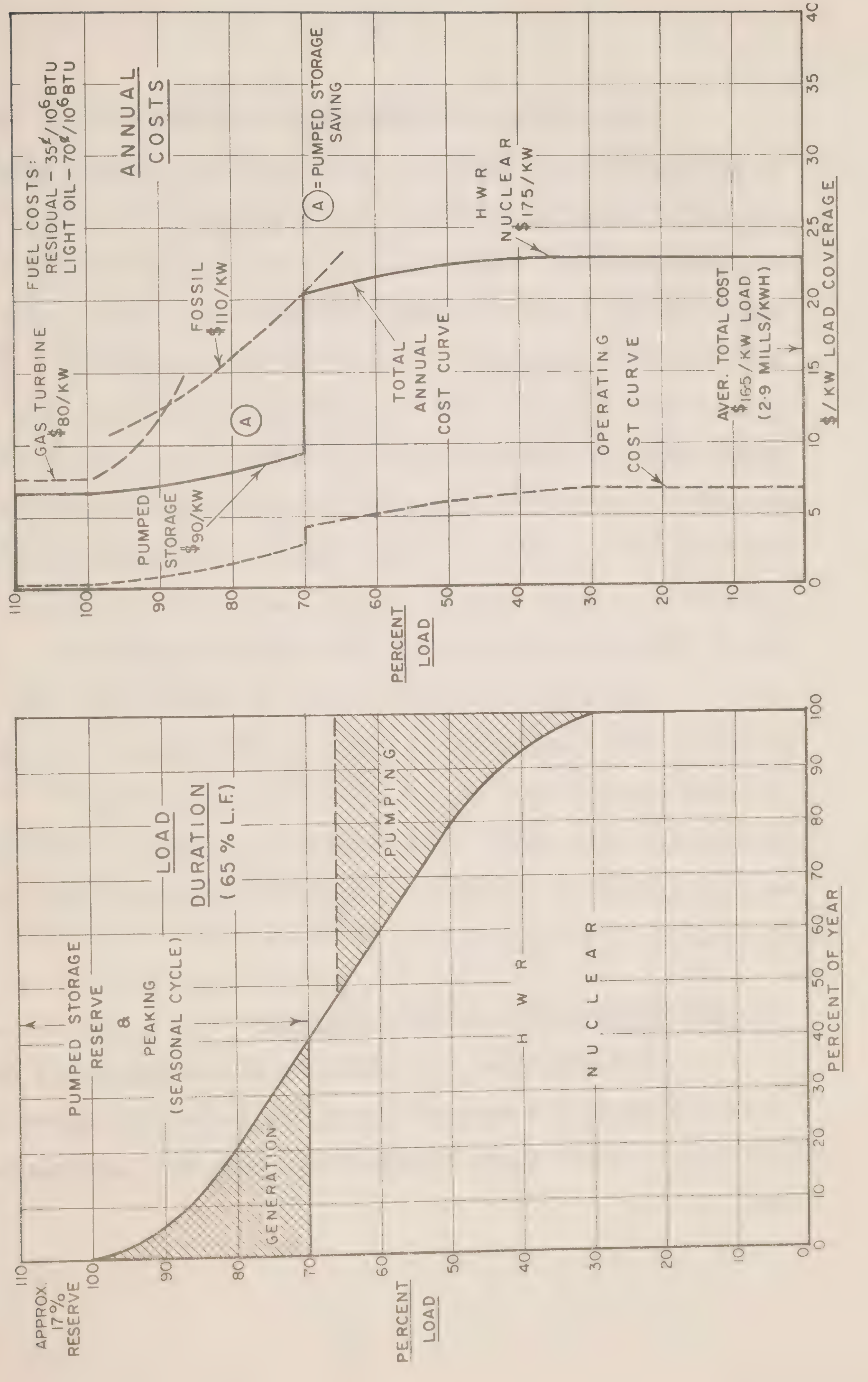


FIGURE 13

GENERATION MIX – FUTURE HWR SYSTEM
WITH $90/KW PUMPED STORAGE



Because system expansions will require the retention of existing fossil units and gas turbines, a future generation mix would never be as "pure" as developed in the above analysis of fixed systems. The future role for pumped storage therefore may not be as great as indicated above. The analysis does, however, raise the obvious questions - how many pumped storage sites are available? What are the pumped storage capital costs? Would there be enough pumped storage to maintain a pumped storage/nuclear system expansion? The economic and physical practicality of pumped storage on individual systems will ultimately determine the extent of the future development of this type of generation.

The above analysis serves to demonstrate the potential for reductions in total system generation costs in cases where pumped storage can be developed in conjunction with heavy water nuclear generation. The complementary nature of the system characteristics of these forms of generation is apparent.

10. HWR NUCLEAR IN LOW-COST FUEL AREA

The graphical method of total cost analysis can be used to show the possibilities for installing heavy water reactors in areas where fossil fuel costs are comparatively low.

If we assume a fuel environment with a coal price of 17¢ per million BTU and a gas price of 30¢ per million BTU Figure 14 shows the generation mix that would result assuming the available generation is $175 per kw heavy water reactors, $115 per kw fossil units and $80 per kw gas turbines. Note that as base generation the fossil generation cost is only slightly higher than the HWR generation cost. The generation mix is approximately 40% HWR nuclear, 35% fossil generation, and 25% gas turbines. The average system annual cost is $17.5 per kw load or 3.1 mills per kwh.

If we assume that $90 per kw pumped storage is available the generation mix changes dramatically as shown in Figure 15. When more nuclear generation is added to provide pumping energy the pumped storage annual cost curve eliminates the fossil generation and the gas turbines. Installing the additional nuclear generation results in a cost penalty at "A" relative to fossil generation costs, but this penalty is offset by the saving at "B" of the pumped storage costs relative to the fossil and gas turbine costs, to result in a net saving with the pumped storage/ nuclear system. The average system annual cost if $16.5 per kw load or 2.9 mills per kwh.

FIGURE 14

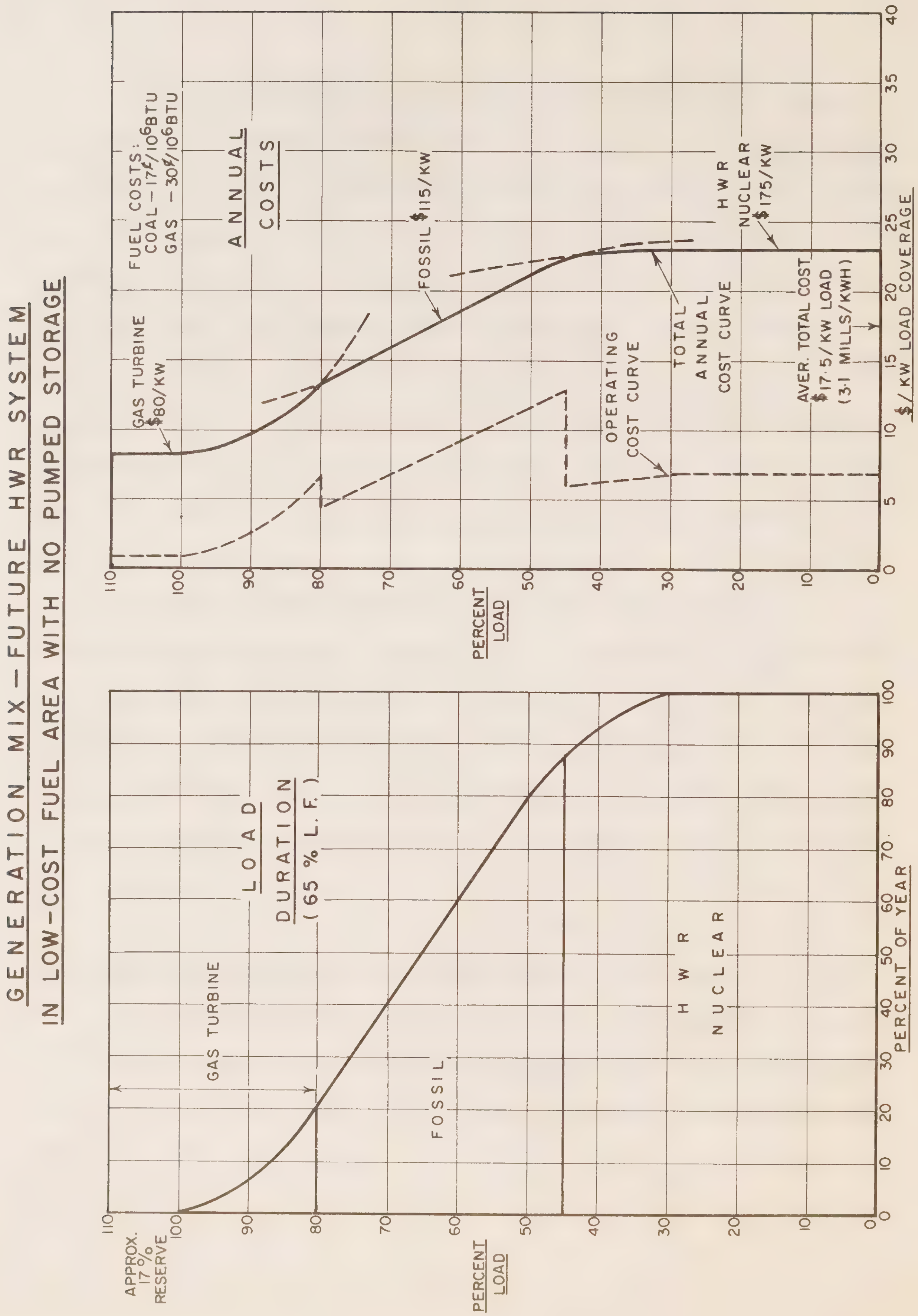
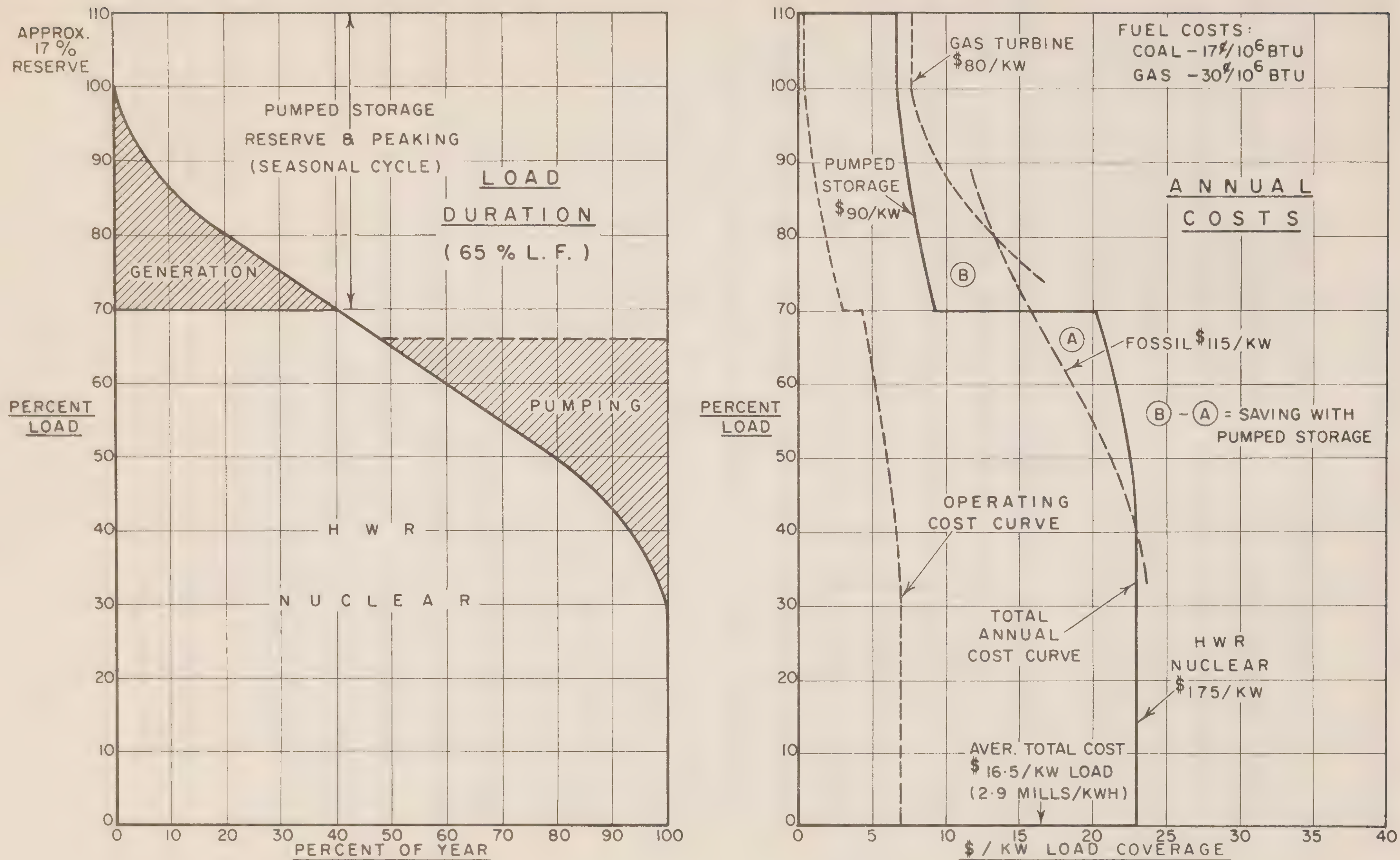

GENERATION MIX — FUTURE HWR SYSTEM
IN LOW-COST FUEL AREA WITH NO PUMPED STORAGE
LOAD
DURATION (65 % L. F.)
GAS TURBINE
FOSSIL
HWR
NUCLEAR
APPROX. 17 % RESERVE
PERCENT LOAD
PERCENT OF YEAR
ANNUAL
COSTS
FUEL COSTS:
COAL – 17¢/10⁶BTU
GAS – 30¢/10⁶BTU
GAS TURBINE $80/KW
FOSSIL $115/KW
HWR NUCLEAR $175/KW
OPERATING COST CURVE
TOTAL ANNUAL COST CURVE
AVER. TOTAL COST $17.5/KW LOAD (3.1 MILLS/KWH)
$/KW LOAD COVERAGE

FIGURE 15

GENERATION MIX — FUTURE HWR SYSTEM IN LOW-COST FUEL AREA WITH $90/KW PUMPED STORAGE



This analysis demonstrates that even in areas where fossil fuel costs are comparatively low pumped storage can enhance the prospects for the installation of heavy water nuclear generation by optimizing the low fueling cost characteristic of the HWR reactors.

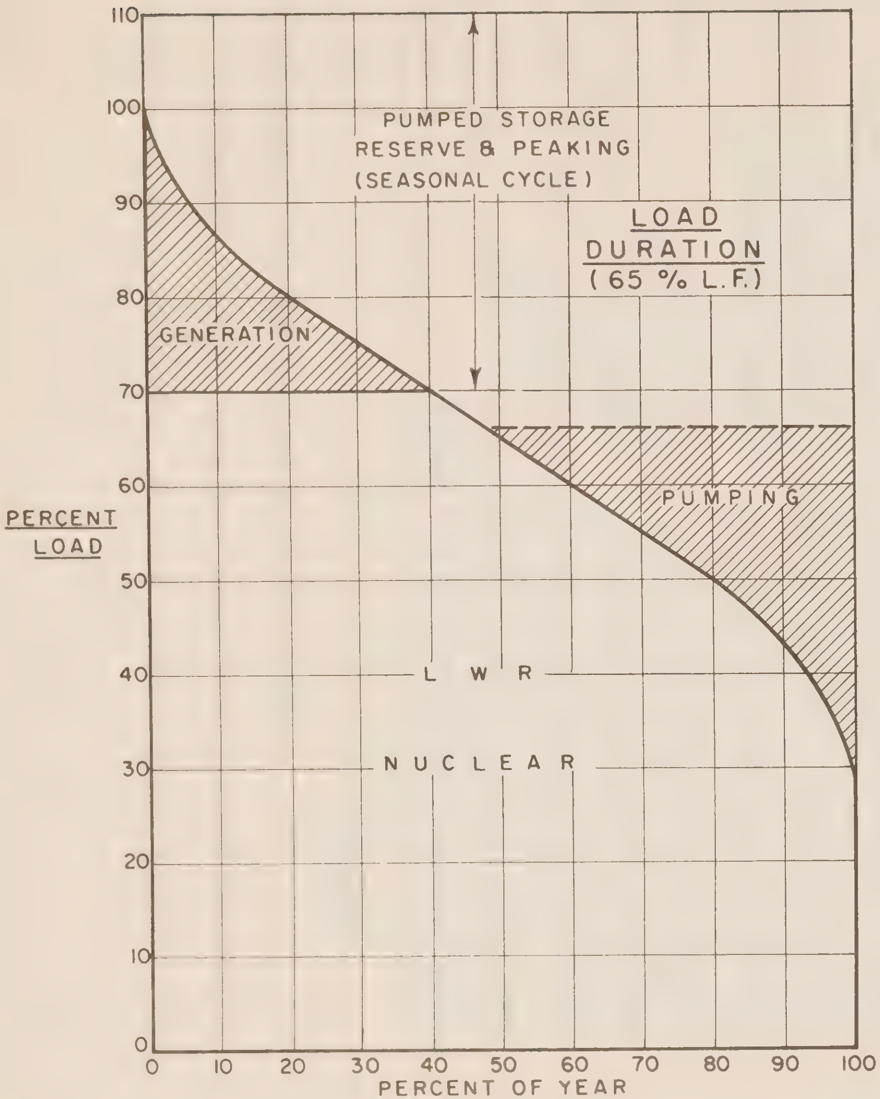
11. COMPARISON OF LWR AND HWR SYSTEMS WITH PUMPED STORAGE

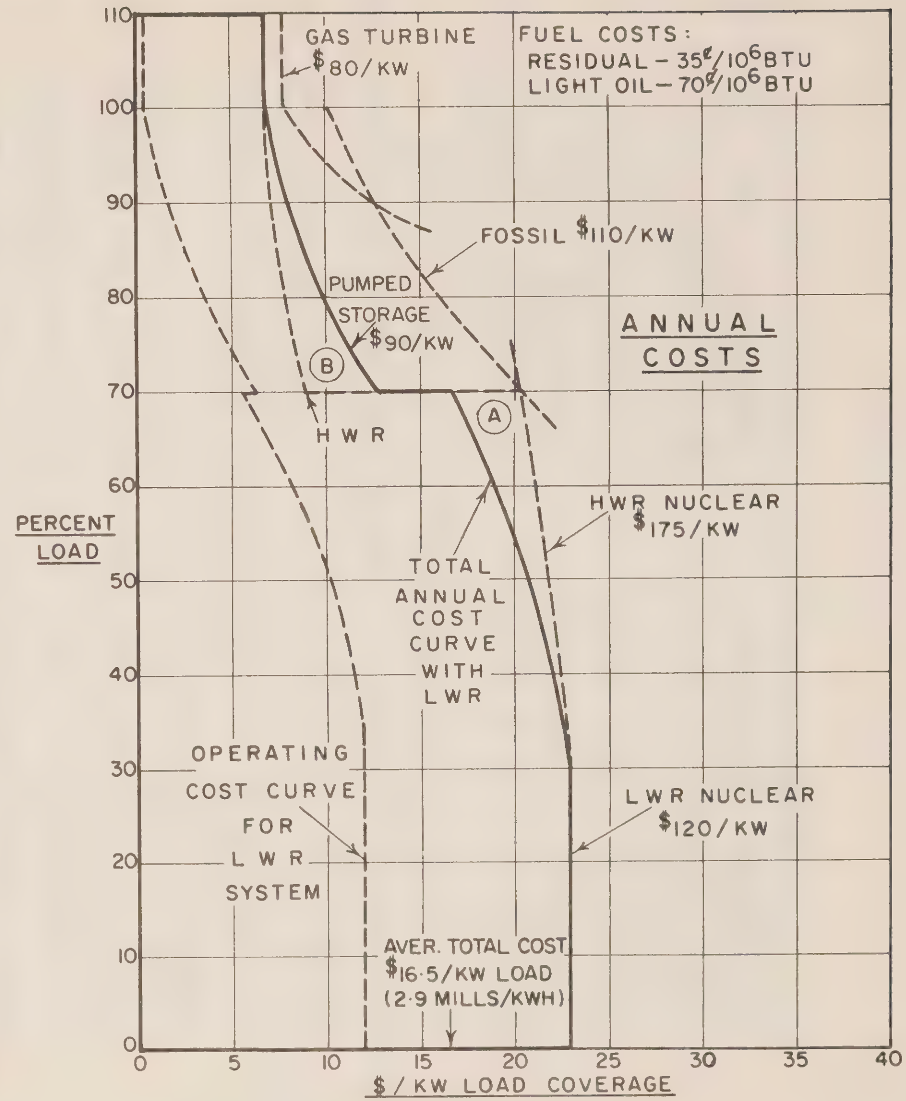
The comparative effectiveness of pumped storage with other types of nuclear generation can be demonstrated by developing the "optimum" generation mix for a light water reactor system as shown in Figure 16. The LWR nuclear generation is assumed to have a capital cost of $120 per kw, a fueling cost of 1.2 mills per kwh, annual operating and maintenance costs of $1.5 per kw and an availability of 87% (15% added to capital costs for scheduled maintenance). The other types of generation are assumed to be pumped storage at $90 per kw, fossil generation at $110 per kw, and gas turbines at $80 per kw. The pumped storage annual costs are less than the costs for fossil generation or gas turbines, as shown in Figure 16, and the generation mix is 65% LWR nuclear and 35% pumped storage. The average system annual cost is $16.5 per kw load or 2.9 mills per kwh.

The LWR cost assumptions, while reasonably close to published cost forecasts, have nevertheless been selected to give base generation annual costs equal to those for the

FIGURE 16

GENERATION MIX – FUTURE LWR SYSTEM WITH $90/KW PUMPED STORAGE





HWR system; the purpose in so doing is to avoid use of these generalized assumptions as a criterion for direct comparison of the two reactor systems. In Figure 16 the comparative total annual cost for the HWR system at a capital cost of $175 per kw is also shown - note that the cost curves in the base generation area coincide. As the capacity factor is reduced the LWR cost is less than the HWR cost (area A), but with pumped storage a greater saving is made when HWR is the pumping source (area B), balancing the penalty at "A".

This analysis indicates that pumped storage can be complementary to all forms of nuclear generation. Heavy water nuclear generation may be economic as base generation, but the ratio of fixed charges to operating charges may favour other reactor types at reduced capacity factors. Pumped storage ensures full loading of the nuclear generation and the resulting economies increase the section of the load curve where heavy water reactors can compete with other reactor types. In this sense pumped storage and heavy water nuclear generation are particularly complementary.

12. SUMMARY

The characteristics of the various types of available generation have been reviewed using a graphical method to analyze power system annual generation costs. This review

has shown that each generation type is best suited to a specific area of the annual load duration curve, dependent on the relationships of capital costs to operating costs.

On future systems nuclear generation with its low fueling cost will provide the base generation except in very-low-cost fossil fuel areas.

Fossil generation will serve as intermediate generation with older units serving as standby reserve prior to ultimate retirement.

Pumped storage is complementary to nuclear generation and, where economic sites are available, it will supply the peaking generation. It may also provide reserve if installation costs are low.

Gas turbines, with low capital costs but relatively high operating costs, will be best suited for reserve and peak-shaving.

Because of the variety of factors affecting the optimum selection of generation mixes it is difficult to generalize on the timing of future generation patterns. Each power system must be analyzed individually on the basis of permissible unit size, fossil fuel costs, pumped storage site availability, existing generation pattern and the potential for conventional hydro.

Expansion of future systems by introducing the most economic type of generation for each section of the load curve will result in substantial savings in system annual generation costs. It is estimated that an average system annual generation cost in the near future may be about $23 per kilowatt of load or 4 mills per kwh, and ultimately may be about $17 per kilowatt of load or 3 mills per kwh, provided of course that there are no substantial deviations from the stated cost assumptions.

The approximate average generation costs for the assumed system conditions reviewed in this study were found to be as follows:

System Conditions	Average Annual Generation Cost Including Reserve	
	Per kw Annual Demand	Per kwh Load
New System		
HWR at $300/kw, fossil at $150/kw, gas turbines at $100/kw, pumped storage at $150/kw	$26.0	4.6 mills
Expanding System		
HWR at $175/kw, fossil at $110/kw, gas turbines at $80/kw, pumped storage at $150/kw	$22.5	4.0 mills
HWR System		
HWR at $175/kw, fossil at $110/kw, gas turbines at $80/kw		
- no pumped storage	$18.5	3.3 mills
- $150/kw pumped storage	$17.5	3.1 mills
- $90/kw pumped storage	$16.5	2.9 mills

<u>Low-Cost Fuel Area</u>

HWR at \$175/kw, fossil at \$115/kw, (coal at 17¢/10^6 BTU), gas turbines at \$80/kw (gas at 30¢/10^6 BTU)		
- no pumped storage	\$17.5	3.1 mills
- \$90/kw pumped storage	\$16.5	2.9 mills
<u>LWR System</u>		
LWR at \$120/kw, fossil at \$110/kw, gas turbines at \$80/kw, pumped storage at \$90/kw	\$16.5	2.9 mills

The foregoing figures assume a 70% cycle efficiency for pumped storage; it is possible that this performance may be improved. In such an event the benefits of the heavy water reactor/pumped storage combination would be increased.

As nuclear generation and pumped storage are added on future systems appreciable reserve capacity will become necessary to permit scheduled maintenance of base generating units. Although system expansions and interconnection additions may decrease the forced outage reserve allowance, the total reserve requirement including the maintenance allowance is likely to remain in the 15% to 20% range. The cost of this reserve capacity will continue to be a part of the annual generation cost.

Although historical lifetime capacity factors for fossil units have been about 40%, it is apparent that they will be substantially decreased on nuclearized systems. This feature alone will tend to decrease the economic feasibility of new fossil units. Accordingly, future fossil unit characteristics will probably emphasize low capital costs and improved operating flexibility at the sacrifice of some operating efficiency.

The existence of older fossil units and the possibility of hydro capacity increases may limit the major use of gas turbines for some time. Thereafter gas turbines will probably supply a large portion of the reserve requirements because of their low capital cost and rapid startup characteristics.

Pumped storage, particularly if it has a seasonal cycle, when associated with heavy water nuclear generation permits the realization of valuable complementary characteristics by allowing the continuous operation of the nuclear generation, thereby taking full advantage of the very low fueling cost of this reactor type. Thus, pumped storage can increase the amount of heavy water nuclear generation that can be economically installed on a power system. These complementary features may enhance the marketability of heavy water reactors where pumped storage sites are available.